AD-775 692

INTERDICTION OF A CAPACITATED LOGISTICS NETWORK

James F. Beaumaster, et al

Air Force Institute of Technology
Wright-Patterson Air Force Base, Ohio

January 1974

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

AD775 692

INTERDICTION OF A CAPACITATED
LOGISTICS NETWORK

James F. Beaumaster, Major, USAF
David P. Robinson, Major, USAF

SLSR 14-74A

161

1.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) GRADUATE EDUCATION DIVISION SCHOOL OF SYSTEMS AND LOGISTICS AIR FORCE INSTITUTE OF TECHNOLOGY, WPAFB, OH	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

INTERDICTION OF A CAPACITATED LOGISTICS NETWORK

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

MASTER'S THESIS

5. AUTHOR(S) (First name, middle initial, last name)

JAMES F. BEAUMASTER, MAJOR, USAF
DAVID P. ROBINSON, MAJOR, USAF

6. REPORT DATE	7a. TOTAL NO OF PAGES	7b. NO. OF REFS
JANUARY 1974	159	19

8a. CONTRACT OR GRANT NO b. PROJECT NO N/A c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) SLSR 14-74A 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) N/A

10. DISTRIBUTION STATEMENT

APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

11. SUPPLEMENTARY NOTES Approved for public release IAW AFR 190-17 Jerry C. Hix JERRY C. HIX, Captain, USAF Director of Information, AFIT	12. SPONSORING MILITARY ACTIVITY SCHOOL OF SYSTEMS AND LOGISTICS WRIGHT-PATTERSON AFB, OHIO 45433

13. ABSTRACT

ATTACHED

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
INTERDICTION						
TACTICAL WARFARE						
TRANSPORTATION						
SUPPLY						
MODEL						

SLSR 14-74A

INTERDICTION OF A CAPACITATED LOGISTICS NETWORK

James F. Beau..aster, Major, USAF
David P. Robinson, Major, USAF

In a tactical war environment, the commander of friendly forces faces a major problem in determining the most effective use of available aircraft sorties. Aircraft can be launched in different roles, such as air superiority, air interdiction, and close air support. The different roles compete for available aircraft resources so that complete satisfaction is rarely attained for each type role. The commander needs a method to determine potential results of sortie application in each of the air roles. The objective of this thesis is to provide a method for determining potential results in one of the air roles, air interdiction of a capacitated logistics network. In an effort to measure interdiction effectiveness, a network model is developed to provide air interdiction planners with an analytical method for reducing enemy supply thruput. The network model represents the tonnage capacity of a ground transportation network; the assignment of interdiction attacks against network targets; and the changes in thruput tonnage, network routes, and thruput costs which result from these interdiction attacks. The model answers two general questions about air interdiction effectiveness: 1) whether or not a capacitated transportation network can be interdicted to reduce flow capacity below enemy supply requirements; and 2) whether or not available interdiction aircraft have a satisfactory probability of attack success. The model is converted to a computer language, FORTRAN, for rapid processing of model variables. A user's guide is included in Appendix A which explains how to input model variables into a remote computer terminal.

SLSR 14-74A

INTERDICTION OF A CAPACITATED LOGISTICS NETWORK

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

By

James F. Beaumaster
Major, USAF

David P. Robinson
Major, USAF

January 1974

Approved for public release
distribution unlimited

id

This thesis, written by

Major James F. Beaumaster

and

Major David P. Robinson

and approved in an oral examination, has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT

DATE: 16 January 1974

Edward J. Fisher
COMMITTEE CHAIRMAN

ACKNOWLEDGMENTS

We wish to express our sincere appreciation to those individuals who assisted in the preparation of our thesis.

A special thanks is expressed to our thesis advisor, Lt. Colonel Edward J. Fisher, for his analytical assistance and constructive criticism during the development phase of this research project. His thorough reading and critique of our draft manuscripts considerably enhanced the final manuscript.

Our gratitude is also expressed to the personnel of the School of Systems and Logistics Computer Operation Section for their assistance with computer programming problems encountered during the study.

Recognition is also due to Mrs. Theda Foster for her assistance in editing draft manuscripts.

A grateful thanks is expressed to our wives, [redacted] and [redacted] for typing the draft manuscripts of the thesis. Also, their continued encouragement, understanding, and sacrifice was a tremendous inspiration for successful completion of the study.

Finally, we extend a sincere thanks to Mrs. Eleanor Schwab for her professional typing of the final copy of the thesis.

TABLE OF CONTENTS

LIST OF TABLES

Table		Page

LIST OF DEFINITIONS

Absorption--A portion of supply thruput needed within a network to maintain and defend the network (also termed network absorption and network support).

Air Interdiction--Air operations conducted to destroy, neutralize, or delay enemy military potential before it can be brought to bear effectively against friendly forces, at such distance from friendly forces that detailed integration of each air mission with the fire and movement of friendly forces is not required (15).

Anti-Capacity Interdiction--Any attack limiting the traffic handling capacity of a channel of movement, such as dropping a bridge span or cutting a rail line (6).

Anti-Goods Interdiction--An attack which denies goods to an opposing force by destroying or damaging stockpiled material, destroying or damaging goods in motion, and forcing increased consumption of goods.

Attacking Unit--One or more sorties assigned to strike one target.

Capacity-Critical Link--A link whose removal from a network produces greatest reduction, or expected reduction, in supply thruput.

Cost--The resource expenditure required to move some quantity of thruput over a link or through a network from source to sink. Cost may be expressed in dollars per ton, dollars per vehicle, man-hours, miles, ton-miles, or any other definable way to compare resource expenditure.

Direction-Oriented Links--One-way links which proceed directly towards the sink node.

General War--That level of warfare involving total national resources in a fight for national survival.

Guerilla Warfare--Small, independent bands of soldiers who use hit-and-run tactics until greater military and/or political power can be attained for their cause.

Invulnerable Link--A link which does not contain a target whose destruction would stop supply thruput.

Link--A segment of a transportation route (such as a road, a railway, or a waterway) between two nodes traversed by vehicles carrying supplies and materials.

Mission--One or more aircraft flying together in a particular airpower role to accomplish a particular task, such as five interdiction aircraft attacking a network target.

Node--A fixed location in a transportation network where supply vehicle movement originates, link of mode of transportation changes, or supply vehicle movement terminates.

Pitched Battle--A battle in which opposing forces have taken up a regular position.

Priority Target List--A list, constructed by interdiction planners, which establishes the order in which network links will be attacked by aircraft.

Probability of Attack Success--The probability one aircraft has of successfully destroying a target on a link and closing that link to supply thruput.

Route--A unique, connected set of links which originates at the source node and terminates at the sink node.

Sensitivity Analysis--An analyst's attempt to determine how susceptible the rank-ordering of alternatives is to changes in variables.

Sink--Terminal node in a transportation network.

Sortie (air)--An operational flight by one aircraft.

Source--Originating node in a transportation network.

Tactical Warfare--That level of warfare fought by military forces without commitment of total national resources.

Thruput--Supply flow through a network.

Two-way Link--A segment of a transportation route which allows traffic flow in both directions by supply vehicles.

Unimproved Road--A road whose surface consists of dirt and rocks.

Vulnerable Link--A link which contains a target whose destruction would stop supply flow.

LIST OF ILLUSTRATIONS

CHAPTER I

BACKGROUND FOR THE NETWORK MODEL

Problem Statement

Interdicting an enemy transportation network comprises a major component of air effort in tactical warfare. Finite aircraft resources prevent a friendly force from striking every conceivable enemy logistics target. Aircraft must also be available for missions involving air defense, air superiority, observation, and close air support. Therefore, the planner of air interdiction strikes must determine how an enemy transportation network can be attacked, with minimal aircraft sorties, to achieve a given level of disruption.

Interdiction strikes should be directed to those targets in the transportation network which provide the greatest measure of effectiveness in terms of reducing supply flow through the network. The target may be a bridge, a tunnel, a waterway, or a convoy of trucks. However, it may be impractical to attack every network target that provides a significant reduction in supply flow. Some targets may be heavily defended; other targets, such as large bridges, may be difficult to destroy. The interdiction planner must have

the capability of determining which targets in the transportation network are most practical to attack. Before these targets are attacked, the planner must know the degree of success expected in light of the physical properties of the target, weapons delivery system, available weapons, and antiair defenses. Additionally, the planner must be able to calculate the effect, in terms of reduced supply flow, that destruction of a target will exert on the overall transportation network.

Background

Dealing explicitly with uncertainty and determining the relative significance of what is known compared to what is unknown are basic problems facing a commander of friendly forces operating in a tactical war environment. The commander has a problem in attempting to determine the optimum use of available aircraft sorties for the most effective strategy. The meaningful application of quantitative analysis can enhance the role of military judgment and experience in the decision-making process by permitting the commander (decision-maker) to focus attention on the essential relationships and critical values of the problem.

> There are usually some objective characteristics of the situation that can be reduced to quantitative techniques. . . . The value of these techniques lies not in giving an answer to the problem, but in eliminating the purely subjective approach based on enthusiasm (1:33).*

---

*The first number in the parentheses refers to the source number in the bibliography; the second number, to the page in the source. (1:33) is Amme's "Crisis of Confidence," page 33.

1. need for quantitative information at the theatre commander level arises from several practical considerations:

1. The resources available for use are limited. Hence, duplication of effort is a luxury which cannot be afforded.

2. The point is eventually reached in air operations at which, in general, relatively large increases in force expenditure may yield relatively small increments in combat effectiveness. Wasteful commitments of resources to targets with only marginal value must be avoided.

3. Because pursuit of the incorrect strategy in conflict situations is both costly and time consuming, care must be taken to assure that sound decisions are reached in day-to-day planning.

Considerations such as these suggest that military planners must be concerned not only if a particular strategy will add to capabilities but also, to the greatest extent possible, how much capabilities will be increased. It is also important to know how effective a particular strategy will be compared with achieving similar results by alternate means. Availability of quantitative information, when used properly in light of the many non-quantitative factors that may be considered, can help insure that the resources available for a theatre commander are most effectively employed in achieving military objectives.

In order to choose among alternatives, a method to estimate and predict the various consequences of selection

must exist. The scheme for doing this may be as elementary as the intuition of a single expert; however, a more formal process usually leads to better results. In recent years, the formal process has involved analytical techniques as decision-making tools. The relationship between analytical problem-solving and modern defense imperatives is natural. Resources are limited. Some level of military effectiveness is fixed. Therefore, attempts are made to determine the alternative which will attain the desired effectiveness at minimum cost, in terms of resources used.

Generally, analytical techniques attempt to solve problems by enlisting the use of a model. The word <u>model</u> in this context means nothing more than a representation of some real world situation. For instance, network modeling and analysis techniques are assuming an increasingly important role in the solution of large transportation problems because of the ease with which a problem can be modeled in network form (13). The basic idea of networking is to separate a large problem into smaller component parts and then to analyze the parts. It is possible to consider the relationship of any part to the whole system and to determine how changes in each part influence the overall large problem (7).

Consider a network comprised of a set of nodes (points which represent the junction of two or more links), certain pairs of which are connected by directed (direction-oriented) links. For example, look at the network in Figure 1.1. In this transportation network, the links (denoted A,B,

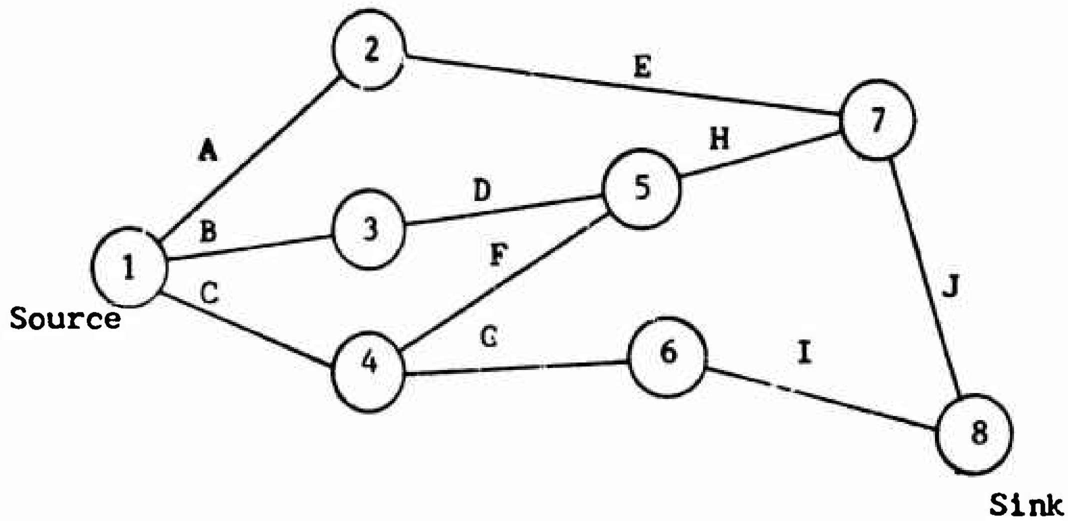

Figure 1.1

Transportation Network

C,D,E,F,G,H,I, and J) may represent roads, railroad tracks, or canals; and nodes may represent cities, railheads, or route intersections. Military planners may be interested in this network from several viewpoints: (1) What is the shortest route from the source to the sink? (2) How much time is taken to traverse a route? (3) What is the maximum steady-state quantity of flow of supplies from the source to the sink?

While time and distance are areas of concern for military planners, ultimately the greatest concern centers about how much quantity can flow through the transportation system. The flow from source to sink is called the <u>network supply thruput</u>. If there is no restriction on the quantity of material flowing through the network, theoretically no limit to the thruput potential of the network exists. More realistically, there exists an upper limit of traffic which

can flow along a link, because of the physical nature of the link. For example, an unimproved road network through rough terrain, which supply trucks use to deliver resources to fighting forces, would restrict the level of supply thruput. Steep grades and a poor road surface would limit truck speed. Truck density is limited by a factor termed <u>traffic discipline</u>. Traffic discipline refers to the interval (time or distance) between trucks maintained by truck convoys traversing network links. The length of an interval is usually based on road conditions; truck speed; and, in a hostile environment, threat of attack by either roadside ambush teams or air interdiction aircraft. The traffic discipline established for a link can become the controlling factor for setting upper limits of supply flow on that link. When such limits on capacity can be established for all network links, the network is termed a <u>capacitated network</u>.

The capacity of the network in Figure 1.1 may be regarded as the tons per hour which flow from the source (node 1) to the sink (node 8) using all the routes, assuming that a specified traffic discipline exists. An <u>anti-capacity</u> interdiction attack consists of dropping ordinance on one or more of the links to reduce the transportation network capacity; that is, to reduce the tons of supplies delivered to node 8. A link can be attacked in several ways: destroying a bridge, closing a tunnel, or cratering a road. If a link is attacked, the amount of traffic-flow may be reduced or even stopped, until the link is repaired.

The intended result, in an anti-capacity interdiction campaign, is to reduce the total amount of supplies which an enemy could use to sustain military operations. An enemy force requires a given level of thruput in a combat area commensurate with military objectives. If the objective is to initiate and sustain an offensive drive, more supplies are needed than if the objective is to hold a defensive position. Additionally, more supplies are needed to actively defend a position than if the battle front is inactive. For example, a study of OPERATION STRANGLE, an independent air operation designed to force the withdrawal of the German armies from central Italy during World War II, revealed that German requirements were 5500 tons per day, when defending against ground assault, and 4000 tons per day, when fighting was not heavy (14:29). Moreover, a large conventional force requires more material (ammunition and weapons) and supplies (food, fuel, clothing, medicine) than a small guerilla force.

Figure 1.2 illustrates some characteristics of anti-capacity interdiction. Assume that an enemy force has been able to move 300 tons of supplies per day through a network which has not been subjected to anti-capacity interdiction. For the sake of illustration, assume the enemy force can sustain offensive action with a thruput level of 150 to 200 tons per day (stockpiling amounts above this). However, the enemy force has decided that, if thruput plus withdrawal from stockpiles drops below 150 tons per day, rationing becomes necessary. Consequently, offensive action must be suspended

in favor of defensive positioning. Furthermore, if total resupply tonnage drops to 50 tons per day, defensive positions must be abandoned and forces must be dispersed into guerilla units for pure survival.

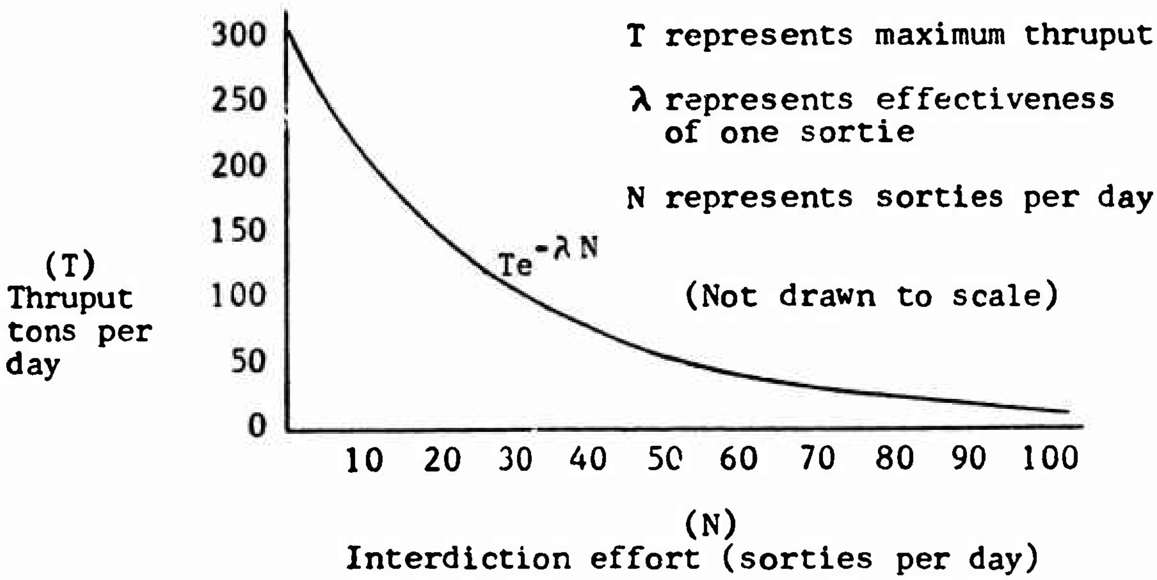

Figure 1.2

Characteristics of a Hypothetical Anti-Capacity Interdiction Campaign

Figure 1.2 gives a general indication of interdiction effort which might be expended in order to exponentially decrease enemy supply thruput to the level where offensive and defensive actions can no longer take place.

For example, with an air interdiction effort of 20 sorties per day and a sortie effectiveness of .035*, network thruput falls just below 150 tons per day. This sustained

*The units of sortie effectiveness are "decimal portion of flow reduction per sortie."

interdiction effort would eventually deplete enemy stockpiles and cause a cessation of offensive action. If air interdiction effort were increased to 50 sorties per day and sustained at that level, the enemy force would eventually be forced to disperse or face possible defeat in a pitched battle.

For the logistics system depicted in Figure 1.2, the interdiction effort can reach the point where continued attack is no longer practical. Note, for example, that beyond 30 sorties of interdiction effort per day, enemy thruput is reduced at a relatively slow rate. At 30 sorties per day, flow becomes 105 tons per day. Doubling interdiction effort to 60 sorties per day causes a further 68 tons per day reduction in thruput (to 37 tons per day). This portrayal assumes a constant repair of destroyed link targets and continued air interdiction effort to keep links closed. Thus, tactical warfare decision-makers may decide that additional interdiction effort beyond 30 sorties per day is an inefficient expenditure of aircraft resources compared to possible use of the aircraft elsewhere.

Since Figure 1.2 depicts the air interdiction-network thruput relationship in a general way, additional factors can be added to the discussion for increased realism. For example, an enemy force could counter anti-capacity interdiction strikes by building alternate routes around vulnerable targets. The enemy also could relax traffic discipline in an

effort to thruput more supplies before links are closed. To illustrate this point, assume the enemy force were able to increase thruput from 300 tons per day to an upper limit of 500 tons per day by exerting maximum effort. Note, in Figure 1.3, that the increased thruput enables the enemy force to continue offensive operations (offensive, defensive, and dispersement supply levels are the same as above) even when interdiction effort is at 60 sorties per day.*

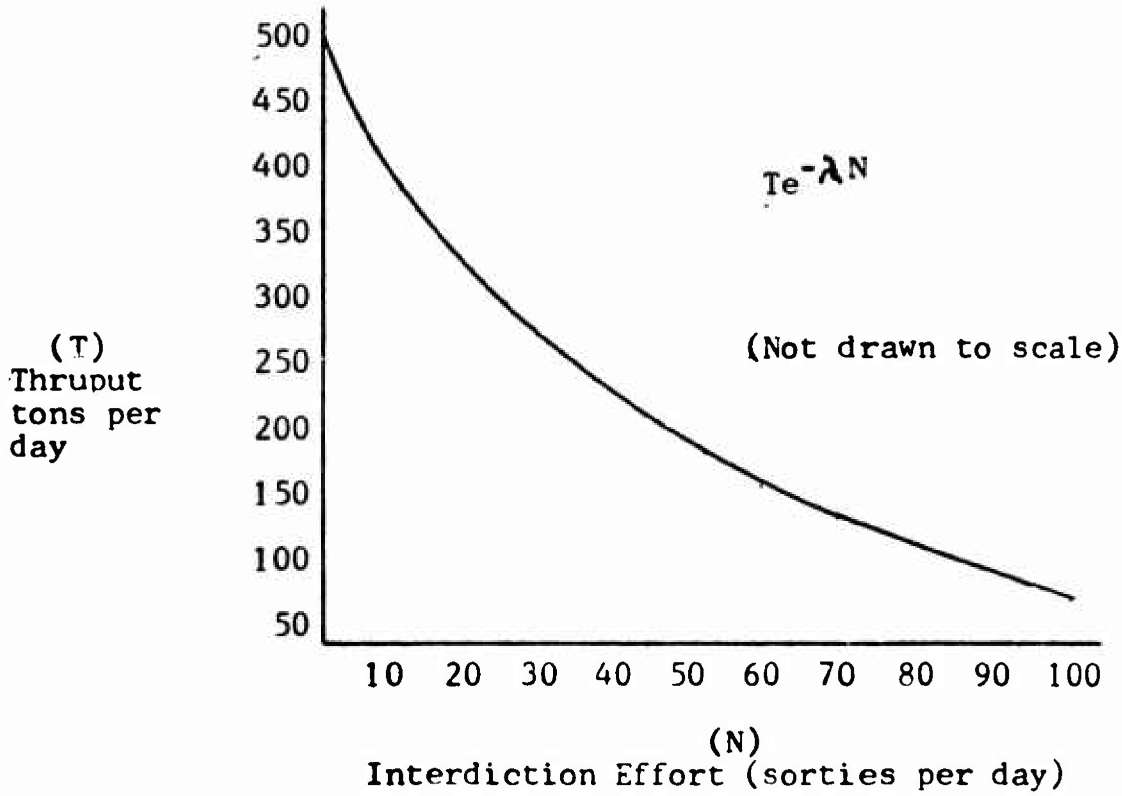

Figure 1.3

Characteristics of Anti-Capacity Interdiction
After Enemy Reaction

---

*Assume that $\lambda = .02$.

Functionally, $Te^{-\lambda N}$ is a predicted effectiveness curve based, say, on average results from previous interdiction experience. Thus, the effectiveness curve changes when operating conditions change or differ from the average. Effectiveness could be expected to change from $Te^{-\lambda N}$ to $Te^{-\lambda_1 N}$, as shown in Figure 1.4, if the enemy established a heavier anti-air defense system to protect vulnerable network targets. Other factors which reduce interdiction effectiveness could be present, such as mountainous terrain, low clouds and poor visibility, malfunctioning aircraft systems, and difficult (hardened) targets. On the other hand, interdiction effectiveness could change from $Te^{-\lambda N}$ to $Te^{-\lambda_2 N}$ if detrimental factors were eliminated and conditions were favorable for accurate, unconstrained bombing.

From Figure 1.4, we may conclude that interdiction campaigns do not ordinarily take place in a static environment. The enemy force may make an "all-out" effort to increase supply thruput as a reaction to air interdiction attacks. In addition, interdiction effort can produce several different levels of effectiveness depending upon operating conditions on a given day. While factors such as enemy air superiority, political havens, and invulnerable targets may increase supply thruput, other factors, such as improved weapons and weapons delivery systems may increase interdiction effectiveness. In this example, then, we have illustrated the basic relationship of network thruput and air interdiction.

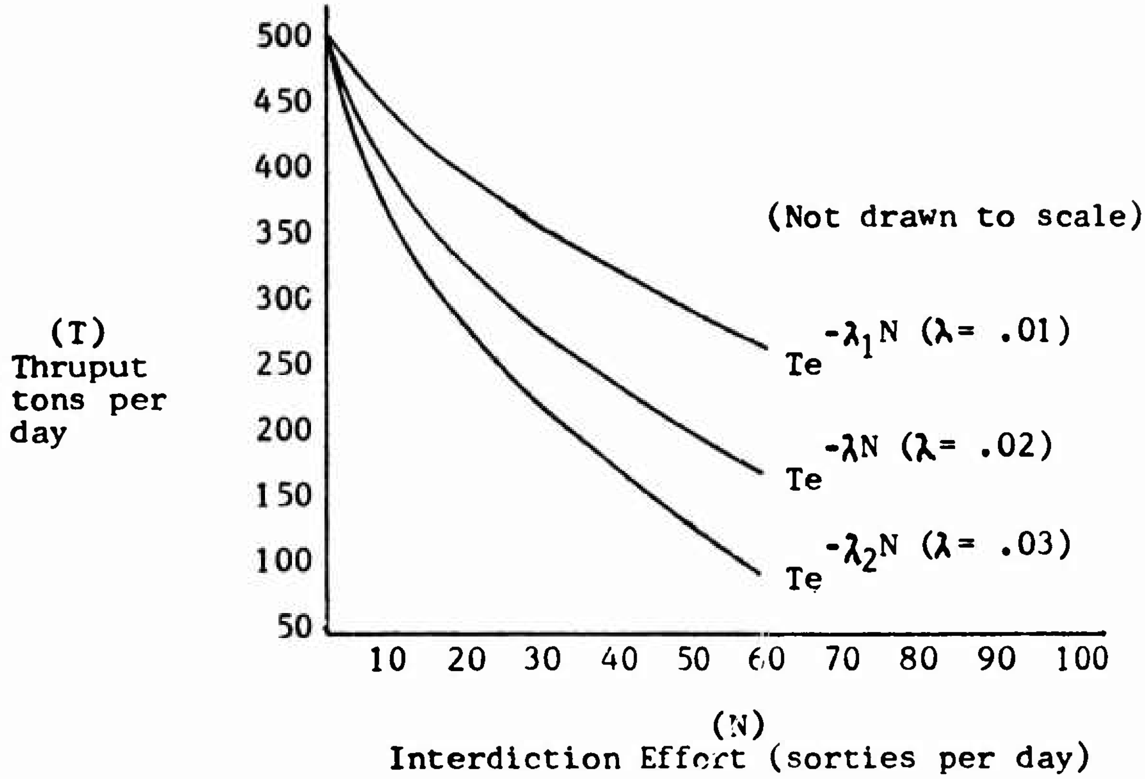

Figure 1.4

Changes in Air Interdiction Effectiveness

Network models have previously been developed to assist military planners in optimizing attacks against enemy supply networks. Durbin (4) outlined a procedure for determining maximum cargo flow as a function of available vehicles and for sequentially selecting and destroying the most vital link in the transportation network until a predetermined number of links are destroyed or until flow is stopped. Wollmer (18,19) developed a method for determining the most vital links in a network, both when flow through the network is limited by the number of vehicles and when it is limited by the network configuration itself. Ashley (2) used a

mathematical model based on two sorties with three possible options to study thruput of a capacitated supply network in a limited war. He used a small nine-link network to keep the analysis within the realm of hand calculations.

Thus, there have been previous efforts to develop analytical tools to assist air interdiction planners. In each case, several components of the problem are approached; however, other aspects are left to the intuition of the decision-maker. With an abundance of experience in the area of tactical air operations, there is a tendency to reject simple models as not being realistic. Complex models are usually rejected as too unwieldy and complex to understand (12).

Strike planners require the assistance of analytical tools in order to perceive complex problems more clearly. However, planners need these tools properly packaged in one computer model that considers multiple aspects of the anti-capacity problem.

This thesis continues the work of Ashley (2) by investigating the application of multiple sorties against larger, two-way link networks. While maintaining the objective of enemy thruput reduction, the possible network target combinations which most practically achieve that objective will be determined. The inclusion of realistic factors, such as two-way links, larger (say, thirty-link) networks, anti-air defenses, and multiple sorties, causes a network problem to become very tedious and time consuming when accomplished

by hand calculation. Therefore, we have developed an analytical method to perform these tedious calculations and quickly display necessary information for interdiction mission planning.

CHAPTER II

THE ANALYSIS PROCESS

Delimitations

We have restricted the scope of our thesis to the scale of conflict termed <u>tactical warfare</u>. <u>Guerilla warfare</u> is not considered because air interdiction may not be able to hamper small independent bands of soldiers. Analyzing air interdiction in general warfare, though useful to contingency strategists, would greatly broaden network model-building. Sufficient research time was not available to broaden the scope of study beyond tactical warfare. Furthermore, we felt more comfortable working with a tactical warfare scenario, since our warfare experience is based on tactical air operations in Southeast Asia.

Interdiction strategy in this thesis is not based on the classic notion of isolating an enemy force from a source of supply, rather <u>interdiction</u> is defined in terms of the strain imposed upon an enemy when supply flow is inadequate to carry on a specified level of activity. An assumption here is that intelligence-gathering agencies are generally able to determine what effect thruput reduction exerts upon enemy operations. Two specific interdiction strategies,

anti-capacity interdiction and anti-goods interdiction, are used in the thesis. Anti-capacity interdiction refers to attacks which limit the traffic handling capacity of a channel of movement, as discussed in Chapter I. Anti-capacity interdiction strategy is used in our FORTRAN based computer program discussed in Chapters III and IV and provides the major topic of the thesis. Anti-goods interdiction denies an enemy sufficient quantity of material to meet demands for goods: for example, destruction or damage of goods in transit; forcing increased consumption of goods, such as air defense activity; destruction or damage of stockpiles; and forcing replacement of goods, such as trucks. The network model for a computer simulation example in Appendix B is based on an anti-goods interdiction strategy, although stockpiles of supplies and materials are not attacked. Other specific interdiction strategies, such as anti-capability (attacking oil and petroleum sites, equipment repair facilities, and vehicle inventories) and anti-defense (attacking AAA sites, missiles sites, and electronic counter-measure facilities), are not featured in our network model. We concentrate primarily on anti-capacity interdiction.

It is not always possible to completely destroy each interdiction target, due to the physical size or nature of some targets. Interdiction strikes sometime succeed in only damaging such targets. The concept of damaged-targets is not addressed in this thesis in order to keep the network model from becoming too complicated. In the context of this thesis,

destruction of a target, such as a link, indicates complete stoppage of supply flow on that link until the link is repaired. A damaged link would not be completely closed, and some percentage of supply flow would occur. The more difficult aspect of damaged-targets is a worthy subject for follow-on studies.

Link repair time and link repair cost are also excluded as elements of the model constructed in our thesis. Link repair time is defined as the time required to restore a link to its original capacity. It is an interesting consideration because it provides information to interdiction planners for link restrike considerations. Link repair cost refers to cost estimates for actual link repair and re-routing supply vehicles caught behind destroyed (closed) links.

Assumptions

Several assumptions are made in our thesis which enable us to construct and work with a network model. Our most basic assumption is that we can accurately depict network nodes and accurately define network links which are representative of actual networks. For example, we assume that a link can be defined by its capacity to flow supplies, the cost to use that link, the reduction in supply thruput to use that link (absorption), and an associated probability to destroy that link. Cost to use a link is related to its length, truck travel speed, and operating and maintenance requirements.* Except for length, all of the elements listed

*Usually, dollar costs are not available to the interdiction planner.

above may be difficult to define in actual situations, due to changes in the environment. For instance, heavy rains may cause a precipitous slowdown in truck travel speed. At best, link capacity, link cost, link absorption, and probability of link destruction are estimates. However, we assume that an interdiction planner can use these estimates confidently and obtain meaningful results.

While we do not attempt to define a node's characteristics in this thesis, we assume that accurate depiction is possible. We assume that a node can be plotted relative to its exact location in the network. Such accuracy may not be possible in actual situations.

Another assumption is that source and sink nodes are inappropriate for interdiction strikes even though, in the model network, they may appear to be more lucrative targets than network links. Source and sink nodes represent general areas rather than specific targets, and their destruction would be appropriate in models which include attack of stockpiled materials. Furthermore, source and sink nodes would tend to be more heavily defended and, therefore, more expensive to strike.

The final assumption we make is that thruput supply flow is network-limited and not limited by the number of vehicles or the quantity of supplies at the source node. When an estimated capacity is assigned to a link, we assume that a network user has sufficient vehicles and supplies to attain maximum link capacity; that is to say, we are indifferent to his inventory of vehicles.

Objectives

In a tactical war target system, the air interdiction planner faces a major problem in determining the optimal use of available aircraft sorties. The planner requires a method to determine potential results of sortie applications against enemy supply networks. In an effort to measure interdiction effectiveness, a network model can be developed to provide the planner with an analytical method for reducing thruput in a capacitated supply network. The network model we developed represents the tonnage capacity of a ground transportation network; the assignment of interdiction attacks against network targets; and the changes in flow capacity, network routes, and costs which result from these interdiction attacks. The model is designed as a quantitative aid which answers two general questions about air interdiction effectiveness:

1. Whether or not a capacitated transportation network can be interdicted to reduce flow capacity below enemy supply requirements.
2. Whether or not available interdiction aircraft have a satisfactory probability of attack success.

Approach

The analytical technique of network modeling has been suggested as a valuable tool in solving complicated logistics problems (3,8,11). At least two reasons support the role of network modeling as a key element in analyzing logistics problems:

1. Network models focus on resolving problems pertaining to distribution of supplies and materials.

2. Network modeling allows a systematic examination of each possible outcome from alternative methods of task accomplishment.

Wagner (17:135) explains that the key justification for using network models is that

> . . . the mathematical characteristics of network models are so special that by exploiting these structural properties you can obtain major efficiencies in finding optimal solutions. . . . network models often contain thousands of activities and hundreds of constraints, so that using a streamlined algorithm is not only worthwhile but sometimes a practical necessity. By investigating networks, you also benefit from seeing how a variety of apparently disparate operations research models are amenable to an insightful unifying mode of analysis.

The approach to problem solution in our thesis generally follows the stages that two authors (10,17) list as standard in applying quantitative analysis. The following is a list of these stages with applicable comments:

1. Formulating the problem. Formulating the problem implies isolating the issues involved, clarifying objectives, and stating the variables. Objectives and issues were covered earlier in the paper, but model variables have not been specifically identified. Model variables are related to two functions: network thruput and air interdiction.

Network thruput variables are:

a. Feasible routes;

b. Link capacities;

c. Link costs;

d. General network absorption.

Air interdiction variables are:

a. Capacity-critical links;

b. Probability of success for attacking aircraft;

c. Number of aircraft available to attack a target;

d. Anti-air defense;

e. Network defense absorption.

2. Building the model. The role of a model is to provide a systematic method of obtaining cost and effectiveness estimates for feasible alternatives. Models are representations of reality; therefore, the appropriateness of a model is not necessarily a function of complexity but rather a function of how well the model represents actual phenomenon. Consequently, a model should incorporate these key variables which its analysts indicate to be of importance.

The network model, constructed in this thesis, appears relatively simple because we set the goal of computerizing the entire model. To fulfill our objective, the model was constructed using the "building-block" concept. This means that the most basic part of the model was computerized; then key variables were singly added to the computer program until the model achieved its final form. By following this technique, however, those key variables added could not be all-encompassing in scope and application but were developed to fit specific situations. This causes certain consequences which must be

mentioned.

First, there can be no assurance that the model presented will produce actual results which are predicted or expected. Actual situations may not be constrained in the same fashion or proportion as model variables are constrained in a computer program. Dynamic features not in the model, such as morale, courage, leadership, and accidental occurrence, are important and could override expected results from the model. Additionally, no matter how detailed a model is constructed, uniqueness of conflicts and activities within the tactical warfare arena often prevent accurate model building. True interaction among all variables in a conflict arena cannot always be measured. Inevitably, some of these interactions must be minimized or even ignored in order to avoid building a model which is too complicated.

Finally, it is not always possible to obtain accurate data for input into the model. Some data are classified; other data are not available. We restricted our research efforts in this thesis to unclassified information. In spite of the difficulties and consequences mentioned above, we believe that the model we have constructed will be beneficial from the standpoint of increased knowledge and insight concerning one aspect of tactical warfare.

3. Performing the analysis. Outcomes obtained from a model must be interpreted and examined. A cost-effectiveness analysis is conducted for selecting from among the feasible alternatives an alternative to accomplish some specified task. There are two

ways in which cost and effectiveness estimates can be handled:

a. Alternatives with equal effectiveness can be compared in terms of relative cost.

b. Alternatives with identical cost can be compared in terms of effectiveness.

The analysis we perform in this thesis follows the approach stated in (a) above where alternatives with equal effectiveness are compared in terms of relative cost.

Explicit and accurate cost data are not calculated in this paper because of the difficulty in obtaining input data, as mentioned above. Cost references are general and relative; for example, total thruput cost for one route as measured, for instance, by its length in miles, may be compared with total thruput cost for another route.

Effectiveness is also difficult to measure and can be discussed only in terms of relative effectiveness. Fisher (5) developed an algorithm which produces a generalized measure of effectiveness for determining thruput in small capacitated networks. This algorithm is the framework from which our FORTRAN based computer program is built. Chapter III presents Fisher's algorithm, which demonstrates how our FORTRAN program functions, for hand calculation of a small example network. Chapter IV demonstrates our FORTRAN program, with networks beyond simple hand calculations.

4. Validation of results. The tradition of analytical models requires that results be open, explicit,

and verifiable. Applying this to the network model requires that all calculations, assumptions, and data be subjected to checking, testing, and possible rejection. We validate the model developed in this study with a sample problem given in Chapter III, where results can be checked by hand calculations. This method of validation seems appropriate for the kind of problem involved. Other methods of validation, such as special data collection efforts, complementary studies, and field testing are possible; but such methods involve longer research times and larger expenditure of funds than were available for this thesis.

CHAPTER III

HAND CALCULATED SOLUTION OF AN EXAMPLE NETWORK

Introduction

The objective of this chapter is to demonstrate a method for determining the thruput potential to a sink from a source through a capacitated network. The example network involves relatively few links, because hand calculations of these networks become tedious as more links are added to the network. The intent here is to show the exact calculations which are pertinent to a computer program we have written to handle the network problem. This computer program is explained in detail in Chapter IV.

The total thruput of supplies reaching the sink of a transportation network is a function of multiple factors. These factors include:

1. The capacity of each link; that is, the quantity of material which may flow out of the link;

2. The number of links and, therefore, the number of feasible routes;

3. The environment with air interdiction present or absent;

4. User capability; that is, sufficient equipment,

men, and material to make use of network capacity;

5. Network absorption; that is, supplies required to operate and defend the network.

In an uninterdicted network, the upper limit of total supply thruput is a function of the number of feasible routes from source to sink, the practical capacity limit of each link, and the user capability to take advantage of thruput capacity.

Figure 3.1 contains an example of a network model. The model consists of four nodes and six links. Circled numbers identify nodes; uncircled numbers identify links.

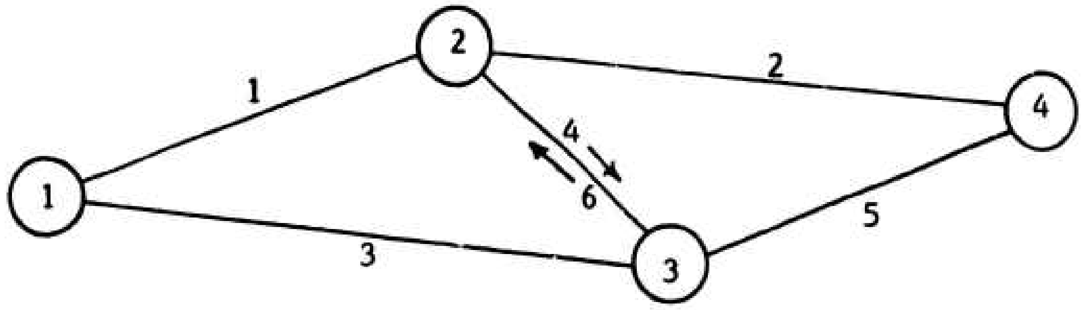

Figure 3.1

Example Network Model

The link between node 2 and node 3 is defined as a two-way link. This means that the user of the network has the flexibility of diverting traffic to link 6 that previously intended to use link 5 to get to the sink. Link 5 may have been closed by natural disaster or wartime interdiction. Two-way links have previously been discussed with network models (2,3,9), but extensive work with them has not occurred

prior to this thesis.

General Procedure

Using intelligence inputs for the practical capacity limit of each link, the steady-state thruput of the capacitated network can be determined by using the network flow algorithm mentioned in Chapter II. The algorithm is as follows:

1. Identify feasible routes from source to sink;

2. Cost each of the routes on the basis of sending one unit of flow from source to sink (costs ≥ 0);

3. Determine the lowest cost route; ties are allowed;

4. For each low cost route, determine available capacity for each of the links in the route;

5. Determine the smallest capacity link in each low cost route;

6. If there are ties in step "3," determine the route with the largest of the small capacities among the low cost routes. If several routes qualify under this step, arbitrarily select one of them;

7. Add to a cumulative "current use" for each link in the route selected in step "6" a quantity of flow equal to the capacity of the smallest capacity link, thereby fully using the smallest capacity link and reducing the available capacity of the other links in the route;

8. For each link in the route, determine the difference between capacity and current use. If the difference

equals zero, the difference will never be negative, increase the unit cost to use the specific link to an arbitrarily large amount (+∞);

9. Having thus adjusted link costs, return to step "2" and proceed through the steps until all route costs become at least as large as the arbitrary amount specified in step "8" (+∞). At this point, the set of "current uses" for links indicates that flow which maximizes thruput;

10. To determine thruput, accumulate the "current uses" of links leading to the sink;

11. We may determine total network costs by accumulating the product of "current use" and unit cost for every link in the system.

The first step in the algorithm is to determine feasible routes through the network. One method is to develop a "FROM-TO" matrix, a square matrix with a row and column number corresponding to each node (5). The source node is represented in the first row and the first column. The sink node is represented by the last row and last column. Other rows and columns correspond to nodes of that particular number. This link identification number is entered in the matrix element that represents the connection from the row "FROM" node to the column "TO" node. Zeros are entered in a matrix element where nodes are not connected by a link. The matrix in Table 3.1 contains the proper entries for the network of Figure 3.1. For example, the number "4" is entered in the element of row 2, column 3, because link 4 emanates from node 2 and terminates at node 3.

Table 3.1

"FROM-TO" Matrix

		To Node 1	2	3	Sink Column 4
From Node	Source Row 1	0	1	3	0
	2	0	0	4	2
	3	0	6	0	5
	4	0	0	0	0

To determine the feasible routes of the network, start at the sink node column and work backward through the matrix to reach the source node row. Starting with column 4, proceed downward from the top until reaching the first link, identifying "2" in row 2. Thus, link 2 is part of a feasible route through the network. Which other links join link 2 as part of that feasible route? The answer is found by observing the row in which the number "2" is found. It is in row 2. Proceed to the column that corresponds to the row number; that is, column 2. Now, scan column 2 downward for a non-zero entry; finding link number "1" in row 1. This joins link number "2" as part of a feasible route. Whenever a link is found in row 1, the source node row, a complete feasible route from source to sink has been found. If a link is not in the source node row, continue the above procedure until reaching a link in the source row. In the feasible route search just completed, the first feasible route uses links 1 and 2.

The search now continues for remaining feasible routes in the network. Since the last search stopped at column 2 the procedure is to continue scanning column 2 for other non-zero entries. The purpose of this procedure is to determine which other links connect with link 2 for a feasible route. In this case, link 6 is the next non-zero entry found. Since link 6 was found in row 3, column 3 is now scanned downward from the top for non-zero entries. The number "3" is found in row 1. This means that another complete feasible route has been found for the network. This route uses links 3,6, and 2 and is the second feasible route found.

Since the last non-zero entry was located in column 3, that column is scanned downward further for other non-zero entries. The next entry, link 4, is found in row 2. Note, however, that link 4 is on the same link with link 6. This means that link 4 must be disregarded in this circumstance, since it would be foolish to proceed along link 4 and then turn around at node 3 to use link 6. Column 3 is scanned further for non-zero entries, and none are found. The procedure is to return to the column which was scanned immediately before column 3 was scanned. Thus, the search proceeds to column 2 where the previous scan stopped with selection of link 6. Column 2 is searched further for non-zero entries below link 6, and none are found. The search goes back to the column used previous to column 2. This moves the search to column 4, where link 2 was previously selected. Searching below link 2, the number "5" is found (link 5). Link 5 is in row 3; therefore, we move to column 3 to look for links that

can connect with link 5 for feasible routes. In this case, the number "3" is found in column 3, row 1. This is the third feasible route for the network. Column 3 is scanned further, and link 4 is found in row 2. Column 3 is left for column 2, where link 1 is once again found. Link 1 is combined with links 4 and 5 to be the fourth and final feasible route through the network. These feasible routes are shown in Table 3.2.

Table 3.2

Feasible Routes

Route	Links in Route
1	1-2
2	3-6-2
3	3-5
4	1-4-5

The hand calculation method for determining feasible routes becomes tedious and time consuming as network size increases. A square grid network of 34 two-way links would generate 184 feasible routes. By using the FORTRAN based computer program we have written, these 184 feasible routes will be determined and printed out in less than 20 minutes.

The second step in the algorithm is to cost each of the feasible routes on the basis of sending one unit of flow from source to sink. Cost can be flexibly stated; that is, in terms of dollars per ton, dollars per ton-mile, miles,

ton-miles, or any such method. For the example network problem, cost will be stated in dollars per ton. Table 3.3 lists arbitrarily selected costs for each corresponding link.

Table 3.3

Link Costs

Link	Cost (dollars/ton)
1	15
2	25
3	25
4	20
5	10
6	20

Following the procedure listed above in step "2" of the algorithm, we calculate the cost of each feasible route in Table 3.2 on one unit of flow from source to sink, as shown in Table 3.4.

Table 3.4

Route Cost

Route	Links	Cost (dollars/ton)
1	1-2	40
2	3-6-2	70
3	3-5	35
4	1-4-5	45

The lowest cost route for this network is route 3, followed by routes 1, 4, and 2. By this priority arrangement, as many tons of supplies as possible will be sent over lower cost routes. In cases where many feasible routes are possible, it is often found that some high cost routes are never used. At this point, step "3" of the algorithm is also complete; that is, the lowest cost route has been determined.

Since route 3 is the low cost route, the procedure now, using step "4" of the algorithm, is to determine available capacity for each of the links in route 3. Available capacity is defined as that portion of maximum link capacity which can be sent along a route from source to sink. This definition is required because the maximum flow along a route from source to sink is constrained by the lowest link capacity in the route. Therefore, in any route, only the lowest capacity link will have its maximum capacity filled. Other links on the route will still have some capacity remaining.

Maximum link capacity for a network will come from intelligence agencies or other experienced personnel. For this example network problem, assume intelligence sources produced the maximum link capacities shown in Table 3.5.

Table 3.6 shows the insertion of the appropriate maximum link capacities into the lowest cost route determined earlier, route 3.

The smallest capacity link for route 3 is link 3. This means that 60 tons per hour is the available capacity for route 3. Link 3 is used to its maximum capacity, while link 5 has 30 tons per hour capacity remaining. Step "5"

Table 3.5

Maximum Link Capacities

Link	Maximum Capacity (tons/hour)
1	90
2	50
3	60
4	10
5	90
6	20

Table 3.6

Lowest Cost Route Capacities (tons/hour)

Route	Maximum Link Capacities	Smallest Link Capacity
3 (links 3&5)	60-90	60

of the algorithm has now been accomplished.

If two or more routes had tied in step "3" of the algorithm, where lowest cost routes were determined, that tie would be broken by the procedure listed in step "6." This procedure examines the links in each low cost route and selects the route with the largest of the small capacities. If the tie is not broken by this procedure, arbitrarily select a route to continue the algorithm. In the example network problem, we encounter no ties.

For step "7" of the algorithm, Table 3.7 is constructed to demonstrate "current use" capacity for each link in the route selected in step "6." Remaining available capacity refers to the maximum capacity still remaining in a link after maximum route capacity has been filled.

Table 3.7

Capacity Flow for Route 3 (tons/hour)

Link	Unit Cost	Current Use	Remaining Available Capacity
1		0	90
2		0	50
3	9999	60	0
4		0	10
5		60	30
6		0	20

"Unit cost" in Table 3.7 is used in the context of maximum dollars that can be spent for a particular link. If remaining available capacity is zero for a link, that link is carrying maximum possible capacity and the cost for that link is at its maximum level. In the example network, 9999 is used to represent maximum unit cost.* Step "8" of the algorithm is now complete; however, one point must be made before proceeding with the algorithm. Link 3 of route 3 is flowing

*We use this simply as a signal that further use of link 3 is not possible.

supplies at maximum possible capacity. This means that any other route which contains link 3 is now eliminated from further consideration for assignment of current use capacity. Thus, route 2, which used links 3-6-2, cannot be used to send supplies through the network. The procedure is to assign the arbitrary, high unit cost, 9999, to route 2. Table 3.8 demonstrates the newly adjusted costs for each feasible route.

Table 3.8

Adjusted Route Costs

Route	Links	Cost (dollars/ton)
1	1-2	40
2	3-6-2	9999
3	3-5	9999
4	1-4-5	45

Having thus adjusted route costs, the procedure, step "9," is to return to step "2" and proceed through the steps until all route costs become at least as large as the arbitrary amount, 9999, specified in step "8." Table 3.8 reveals that route 1 is now the lowest cost route, at $40.00 per ton. Table 3.9 shows current use capacity and remaining available capacity as a result of selecting route 1.

Employing route 1 has used link 2 to its maximum possible capacity. Link 1 still has 40 tons per hour capacity remaining as a result of capacity assignment. Any other feasible routes using link 2 would have been eliminated from

Table 3.9

Capacity Flow for Route 1 (tons/hour)

Link	Unit Cost	Current Use	Remaining Available Capacity
1		50	40
2	9999	50	0
3	9999	60	0
4		0	10
5		60	30
6		0	20

further capacity assignment and a unit cost of 9999 applied. Table 3.10 shows the newly adjusted route costs for all the feasible routes.

Table 3.10

Adjusted Route Costs

Route	Links	Cost (dollars/ton)
1	1-2	9999
2	3-6-2	9999
3	3-5	9999
4	1-4-5	45

Examination of Table 3.10 reveals that only route 4 remains for capacity assignment. Route 4 uses links 1-4-5 with applicable remaining capacities of 40-10-30 tons per

hour. Table 3.11 demonstrates the assignment of capacities to route 4.

Table 3.11

Capacity Flow for Route 4 (tons/hour)

Link	Unit Cost	Current Use	Remaining Available Capacity
1		50+10=60	30
2	9999	50	0
3	9999	60	0
4	9999	10	0
5		60+10=70	20
6		0	20

Adjusted route costs for every feasible route is now at least as large as the arbitrary amount, 9999. No more routes remain to receive capacity assignment. At this point, the set of "current uses" for all six links reflects a flow which maximizes thruput. By adding the sum of the current use capacities of those links which lead to the network sink, links 2 and 5, the thruput of the network is determined, 50 + 70 = 120 tons/hour. This completes step "10" of the algorithm. Total network cost is determined in step "11," by accumulating the product of final current use flow from Table 3.11 and unit cost for each link in the network.

Table 3.12 shows final network cost.

Table 3.12

Total Network Cost

Link	Final Current Use	X	Cost (dollars/ton)	=	Link Cost
1	60		15		$ 900.00
2	50		25		1250.00
3	60		25		1500.00
4	10		20		200.00
5	70		10		700.00
6	0		20		0.00
			Total Cost		$4550.00

The Effect of Interdiction

Up to this point, discussion has centered about maximum supply thruput in a non-interdiction environment. The addition of air interdiction as a thruput variable produces significant changes. Before an attacking unit can be scheduled for an air interdiction mission against a transportation network, a specific target must be selected within the network. The objective is to destroy links in the order of greatest reduction in thruput. In order to determine which links cause the greatest thruput reduction, we remove each individual link; simulate destruction; and calculate thruput for the reduced network. The example network, Figure 3.1, has six links. Removing each link, one at a time, identifies six different, five-link networks. The algorithm used to determine network thruput in the original network has to be

used six times to accomplish the link removal procedure. In the interest of brevity, six more iterations of the algorithm are not presented. Instead, Table 3.13 summarizes the reduction of network thruput resulting from the removal of each link.

Destruction of link 5 causes the greatest reduction of thruput. Therefore, link 5 is termed the capacity-critical link of the example network. For this problem, we assume that destruction of link 4 does not automatically mean destruction of link 6, or vice versa. The nature of the two-way link may be such that two-way traffic reverts to one-way traffic. If there were no other factors to consider and there were 100 percent assurance that the attacking unit would destroy the link, link 5 would be the best target in the network.

Table 3.13

Reduction of Thruput by Removal of One Link

Removed Link	Reduced Network	Surviving Thruput (tons/hr)	Thruput Reduction (tons/hr)	Total Thruput Cost (dollars/hr)
1	2-3-4-5-6	60	60	$2100.00
2	1-3-4-5-6	70	50	2550.00
3	1-2-4-5-6	60	60	2450.00
4	1-2-3-5-6	110	10	4100.00
5	1-2-3-4-6	50	70	2000.00
6	1-2-3-4-5	120	0	4550.00

Total thruput cost for each removed link in Table 3.13 shows user's cost to flow supplies from source to sink, given that the particular link is removed. The total thruput cost of a reduced network reflects the relative effect of link removal in comparison to the original network. Because each link removal can potentially cause a different combination of routes to be used, the variety of route cost combinations varies the total thruput cost of a reduced network. Observe the cost of link 6 removal. Since thruput is not reduced for link 6 removal, total thruput cost remains at $4550.00. Note also that link removal for links 1 and 3 produces the same thruput reduction. However, total thruput cost for these links differs by $350.00. Due to the different costs to flow supplies along each link, this $350.00 difference exists. The difference is useful to interdiction planners because it can be used to break ties between links with like thruput reduction. In this case, link 1 is more attractive to strike than link 3 because, with link 1 removed, it would cost the network user $350.00 more to flow 60 tons per hour from source to sink.

From Table 3.13, a priority target list can be constructed to indicate preference for link attack. This priority target list ranks greatest thruput reduction at the top of the list and proceeds downward to least thruput reduction. From Table 3.13, the priority target list would plan destruction of links 5, 1, 3, 2, 4, and 6, in that order. However, this method of priority target list construction is not

completely useful because it is only valid for destruction of one link, the fi   link. In order to determine the remaining order of links for the priority target list, calculation must be made for removal of a second link, given that the first link is destroyed, followed by calculations for removal of a third link, given that the first and second links are destroyed, and so on until network thruput is reduced to preplanned levels set by interdiction planners. The priority target list above is useful, if the link at the top of the list cannot be attacked due to poor weather, heavy enemy defenses, or other factors. In such a case, alternate links can be selected, based on their position in the priority target list. In the example network problem, for instance, link 5 should be the first link destroyed. If for some reason, link 5 cannot be attacked, link 1 is the alternate link selected for destruction, followed by link 3   he second alternate target. However, this is the only way Table 3.13 is useful for establishing a priority target list.

A more useful way to establish a priority target list is to remove more links, given that previous links had been destroyed. Returning to the example network problem, the procedure is to remove a second link, given that link 5 is destroyed by first strike aircraft. The algorithm used to determine network thruput has to be performed five times on a four-link reduced network. Table 3.14 demonstrates the example network problem for determining greatest thruput reduction with a second link removed, given that link 5 is destroyed.

Table 3.14

Reduction of Thruput for Second Link Removal

Removed Link	Reduced Network	Surviving Thruput (tons/hr)	Thruput Reduction (tons/hr)	Total Thruput Cost (dollars/hr)
1	2-3-4-6	20	30	$1400.00
2	1-3-4-6	0	50	0.00
3	1-2-4-6	50	0	2000.00
4	1-2-3-6	50	0	2000.00
6	1-2-3-4	50	0	2000.00

From Table 3.14, it can be seen that removal of link 2 causes the greatest reduction in thruput. In fact, with link 2 removed, the network is incapable of passing any supply thruput from source to sink. This fact may have been obvious earlier, due to the simple example network discussed; however, as networks become larger and more links are involved, it is not readily apparent how the priority target list will be constructed.

Total thruput cost for the network, with link 2 removed, is now zero, because the user of the network cannot thruput any supplies. This does not mean that total network cost is zero, only that total thruput cost is zero. The distinction is made to reflect the dynamic nature of the user's environment. The user will incur increased total network cost by repairing the damage and increasing protection for network links. The concern of this thesis is with total

thruput cost as a decision-making tool for interdiction planners. The priority target list for this example network, in light of the above discussion, ranks link 5 first, followed by link 3.

Absorption

Previous discussion of network thruput referred to the movement of supplies from the source to the sink. However, every ton of supplies passing through the network cannot be delivered to the sink because personnel, supplies, and equipment are required to maintain and defend the network. Thus, portions of the supplies passing through a network are absorbed by the network to keep the network functional. For example, an anti-aircraft artillery, AAA, site would require a fairly large amount of tonnage to remain active against attacking aircraft. This tonnage, in effect, reduces the final amount of network thruput reaching the sink and can cause a substantial reduction.

Network absorption can be divided into two categories. The first category, termed <u>general network absorption</u>, refers to non-interdiction levels of absorption. This means that a certain quantity of goods is necessary just to maintain a network. Food, clothing, and equipment parts are examples of general network absorption. Once interdiction strikes begin, the second category of absorption is required. This second category, termed <u>network defense absorption</u>, would include such items as ammunition, artillery shells, and anti-aircraft missiles, in addition to general network absorption supplies.

Therefore, the level of total network absorption is a function of the intensity of an air interdiction campaign and the network defender's policy regarding anti-air defense. If the network defender's policy is to fire hundreds of rounds of AAA at every attacking aircraft, large network absorption will result.

It is reasonable to assume that enemy anti-aircraft defense will be heaviest along capacity-critical links which contain highly vulnerable targets. For example, if a link carries a high level of supply thruput which crosses a suspended bridge, the bridge would very likely be heavily defended. On the other hand, if a link carries a high level of supply thruput across a level plain that contains invulnerable targets, enemy anti-air defense would probably be sparse. This means that network defenders would not have to place AAA and/or missile sites along every link. This forces interdiction planners to calculate network absorption based upon the criticality of a link for passing thruput and the link's vulnerability to closure by air interdiction.

Network absorption calculations will be two-phased. The first refers to general network absorption. This allows the interdiction planner to calculate network supply thruput in the pre-interdiction environment. Using the network example problem once again, arbitrarily selected general network absorption will be applied in the amounts indicated in Table 3.15.

At this point, the eleven network algorithm steps are again applied to the problem. Feasible routes and route costs

Table 3.15

General Network Absorption

Link	General Network Absorption (tons/hour)	Link Capacity (tons/hour)	Link Cost (dollars/ton)
1	1	40	$15
2	2	50	25
3	2	60	25
4	1	10	20
5	2	90	10
6	1	20	20

are the same as before in Tables 3.2, 3.3, and 3.4. The lowest cost route, with its corresponding capacities, is shown in Table 3.16.

Table 3.16

Lowest Cost Route Capacities (tons/hour)

Route	Maximum Link Capacities	Smallest Link Capacity
3 (links 3&5)	56-88	56

Table 3.16 shows that link 5 gives up two tons per hour capacity to general absorption; but link 3 must surrender four tons per hour, because link 3 must carry support intended for link 5. As before, link 3 is used to full capacity; and we construct a "current use" table.

Table 3.17

Capacity Flow for Route 3 (tons/hour)

Link	Unit Cost	Current Use	Remaining Available Capacity
1		0	90
2		0	50
3	9999	56	0
4		0	10
5		56	34
6		0	20

Continuing with the selection of low cost routes and assigning available capacity minus absorption, Table 3.18 shows a "current use" table for selection of route 1. Once

Table 3.18

Capacity Flow for Route 1 (tons/hour)

Link	Unit Cost	Current Use	Remaining Available Capacity
1	9999	48	39
2	9999	48	0
3		56	0
4		0	10
5		56	32
6		0	20

again, route 4, using links 1-4-5, is the last remaining route. But, links 1 and 5 have already received general absorption from other routes. Thus, links 1 and 4 of route 4 are only required to carry the general absorption for link 4 (1 ton). The network user wants to supply the operational needs of network links at the lowest cost. Therefore, links 1 and 5 are supplied by previous lower cost routes, while link 4 is supplied by route 4.

Table 3.19 shows the capacity flow for route 4, with absorption added. The "current use" column in Table 3.19 now reflects the amount of thruput flowing along each link enroute to the sink. This illustrates that it is not possible to merely subtract network absorption from network thruput to obtain the effect of network absorption. Notice, also, that link 6 does not receive general network absorption. Link 6 is scheduled for one ton per hour in Table 3.15. Since link 6 is not being used to flow supplies to the sink, its maintenance support requirements are zero.

Before an interdiction planner can apply estimates of network defense absorption, capacity-critical links must be determined and vulnerable targets on links located. Capacity-critical links can be determined by link removal, as before in Tables 3.13 and 3.14. Table 3.20 shows these network defense absorption estimates, combined with general network absorption, to give a final "current use."

Maximum flow arriving at the sink node is now 92 tons per hour, as compared with 120 tons per hour when network absorption was not included in the model. (Recall that

Table 3.19

Capacity Flow for Route 4 (tons/hour)

Link	Unit Cost	Current Use	Remaining Available Capacity
1		48+9=57	30
2	9999	48	0
3	9999	56	0
4	9999	9	0
5		56+9=65	23
6		0	20

Table 3.20

Final Current Use with Network Absorption (tons/hour)

Link	Unit Cost	Total Network Absorption	Current Use	Remaining Available Capacity
1		6	50	30
2	9999	8	42	0
3	9999	8	42	0
4	9999	2	8	0
5		10	50	30
6		2	0	20

maximum flow is determined by adding final "current use" network flow for those links which connect to the sink node; that is, links 2 and 5.)

Removal of the first link in order to find thruput reduction is shown in Table 3.21.

Table 3.21

Reduction of Thruput by Removal of One Link

Removed Link	Reduced Network	Surviving Thruput (tons/hr)	Thruput Reduction (tons/hr)	Total Thruput Cost (dollars/hr)
1	2-3-4-5-6	42	50	$1470.00
2	1-3-4-5-6	50	42	1830.00
3	1-2-4-5-6	42	50	1680.00
4	1-2-3-5-6	84	8	3150.00
5	1-2-3-4-6	42	50	1680.00
6	1-2-3-4-5	92	0	3510.00

From Table 3.21, note that links 1, 3, and 5 are tied for greatest thruput reduction. However, link 1 is the lowest cost link and its removal will cost the network user $1,680.00 to flow 50 tons per hour through links 3 and 5. Given that link 1 is destroyed, Table 3.22 demonstrates removal of a second link. Once again, removal of the second link, link 3, causes the network thruput to fall to zero. At this point, the interdiction planner knows that links 1 and 3 are the critical links for the network. This allows an assumption that links 1 and 3 are heavily defended against air interdiction, provided highly vulnerable targets exist on these links.

Table 3.22

Reduction of Thruput for Second Link Removal

Removed Link	Reduced Network	Surviving Thruput (tons/hr)	Thruput Reduction (tons/hr)	Total Thruput Cost (dollars/hr)
2	3-4-5-6	42	0	$1470.00
3	2-4-5-6	0	42	0.00
4	2-3-5-6	42	0	1470.00
5	2-3-4-6	10	32	700.00
6	2-3-4-5	42	0	1470.00

Probability of Attack Success

The new priority target list for the example network, in light of the above discussion, lists link 1 first and link 3 second. Yet, strict adherence to this new priority target list may not be possible, due to the hostile nature of the air interdiction environment. This environment may contain elements which reduce the chances that a target can be destroyed. In the discussion above, target priority lists were constructed under the assumption of 100 percent assurance (probability equal to 1) that the attacking unit would destroy the link. This is not realistic. Each sortie attacking a target on a link has an associated probability of success in destroying that target. One overall probability can be established for each target(s) that destroys a link. This probability includes such elements as weather in the target area, physical nature of the target, type weapons employed,

weapon delivery capabilities, and anti-air defense capabilities. Air interdiction planners can develop probability factors for these elements based on previous experience and intelligence estimates. A probability factor can be developed for each particular weapons system, using certain type weapons, attacking certain type targets. These probability factors may be difficult to estimate; however, their use provides additional information to interdiction decision-makers for development of a priority target list.

By multiplying the probability factor for each link by the reduction of thruput associated with that link, an expected reduction of thruput is obtained for a one-sortie attack on that link. An example of the use of these probability factors is given in Table 3.23. (The probability factors used are not based on actual research data but are merely examples to demonstrate their use.)

Comparing the results of Table 3.23 with the results of Table 3.21 reveals that link 5 is no longer one of the top priority target links. Links 1 and 3 are now at the top because expected thruput reduction is greater for these links. The tie between expected reduction for links 1 and 3 can be broken by examining total thruput cost data. Since link 3 is more expensive than link 1 for a user of the network, link 1 is selected for destruction first. As before, the final priority target list cannot be prepared until a second link is removed from the network, given that the first link is destroyed.

Table 3.23

Probability of Attack Success Using Table 3.21 Data

Removed Link	Reduction of Thruput by Link Removal (tons/hr)	Probability of Attack Success	Expected Thruput Reduction (tons/hr)	Total Thruput Cost (dollars/hr)
1	50	.7	35	$1470.00
2	42	.6	25	1830.00
3	50	.7	35	1680.00
4	8	.8	6	3150.00
5	50	.5	25	1680.00
6	0	.8	0	3510.00

Assuming link 1 destruction, Table 3.24 shows the final calculations for a five-link reduced network.

Table 3.24

Reduction of Thruput for Second Link Removal

Removed Link	Reduction of Thruput by Link Removal (tons/hr)	Probability of Attack Success	Expected Thruput Reduction (tons/hr)	Total Thruput Cost (dollars/hr)
2	0	.6	0	$1470.00
3	42	.7	29	0.00
4	0	.8	0	1470.00
5	32	.5	16	700.00
6	0	.8	0	1470.00

The removal of link 3 will give the greatest expected thruput reduction and will reduce total thruput cost for the network to zero. This enables construction of a priority target list based upon a one-sortie attack campaign.

The key point about these probabilities of attack success is that their inclusion in the problem has an influential effect upon target priority lists. Admittedly, these estimates can never be more than estimates based upon past experience and/or intelligence estimates; but their use is necessary in order to provide a more realistic solution to the actual air interdiction problem.

Another point that should be clarified is the use of expected thruput reduction in Tables 3.23 and 3.24. Expected thruput reduction is merely a decision-making tool to give appropriate weight to some air interdiction variables. Therefore, if a target is destroyed and a link is removed from the network, actual thruput reduction will be the amount established prior to multiplication by probability of attack success. For example, in Table 3.24, if link 3 is destroyed, actual thruput reduction is 42 tons per hour.

Another approach to reality is including more than one sortie in the attack of an individual target. It would be unrealistic to assume that one sortie can always destroy one target. The nature of the target may be such that several aircraft are necessary to bring about destruction. The addition of more sorties into target attack affects the probability of attack success. The effect of more sorties upon the probability of attack success is an increase in the

probability of success. The formula for probability of attack success, S, would be:

$$p(S) = 1 - (1-p)^n$$

where "n" equals the number of attacking sorties and "p" equals the single sortie probability of attack success.* For example, if the probability of attack success for an individual sortie is .4 and five sorties are flown against one target,

$$p(S) = 1 - (1-.4)^5$$

which is equal to .92. Therefore, by adding more attacking aircraft to the interdiction environment, a greater probability exists that an individual target will be destroyed.

Anti-Air Defenses

So far, the discussion concerning anti-air defenses, as applicable to probability of attack success, has been general. The anti-air defense factor is a function of the criticality of a certain link and the vulnerability of targets on that link. Thus, it may not be possible for air interdiction aircraft to destroy some links without relatively high losses of personnel and aircraft. However, it may be possible for an air interdiction campaign to destroy enough lightly defended links to reduce enemy supply thruput to unacceptable operating levels.

---

*This assumes that each sortie is statistically independent.

A degrading factor for anti-air defenses can be applied to the probability of attack success formula discussed earlier,

$$p(S) = 1 - (1-p)^n$$

Fisher (2:42) includes the degrading influence of anti-air defenses into the probability of attack success formula as follows:

$$p(S) = 1 - (1-ap)^n$$

where "a" denotes the degrading influence. Each independent sortie, "n", is subjected to "m" attempts to prevent attack success; each attempt is independent and has a probability "s" of destroying an attacking aircraft. Then,

$$ap = p\ (1-s)^m$$

and

$$p(S) = 1 - (1-p\ (1-s)^m)^n$$

In the earlier example, p(S) rose from .4 to .92 as the number of attacking aircraft increased from one to five. Now, if each of the attacking aircraft is met by five attempts, missiles for instance, to prevent attack success and each missile has a probability of .1 of destroying an attacking aircraft, the probability of attack success becomes

$$p(S) = 1 - (1-.4\ (1-.1)^5)^5 = .74$$

This expanded formula for calculating probability of attack success is used the same way as before in converting thruput

reduction to expected thruput reduction for decision-makers.

In order to demonstrate how the example network problem is affected by anti-air defenses, we accomplish link removal with the final "current use" thruput established in Table 3.20, following the same procedure used in Tables 3.23 and 3.24.

This example will assume that one aircraft is available to attack each link and that the aircraft can be met by five missiles fired from the ground. Each missile has a probability of .1 of hitting an aircraft. Table 3.25 shows the expected thruput for removal of the first network link.

Table 3.25

Expected Reduction with First Link Removal (Absorption and Anti-Air Defense Included)

Removed Link	Reduction of Thruput by Link Removal (tons/hr)	Probability of Attack Success (*)	Probability of Attack Success (**)	Expected Thruput Reduction (tons/hr)	Total Thruput Cost (dollars/hr)
1	50	.7	.42	21	$1470.00
2	42	.6	.375	15	1830.00
3	50	.7	.42	21	1680.00
4	8	.8	.50	4	3150.00
5	50	.5	.30	15	1680.00
6	0	.8	.50	0	3510.00

*Probability of attack success before anti-air defense for each independent sortie.

**Probability of attack success with anti-air defense included.

The probability of attack success with anti-air defenses included produces a more pessimistic outlook for expected thruput reduction. This may lead decision-makers for interdiction strikes to launch more aircraft against each link in order to raise the probability of attack success. Assume these decision-makers decided to send five aircraft against each link. Each aircraft can be met by five missiles, as before.

From Table 3.26, we see that expected thruput reduction is significantly greater with five aircraft attacking each link. Hence, decision-makers should use sensitivity analysis with this interdiction model in order to arrive at suitable levels of expected thruput reduction. Construction of a priority target list places link 1 at the top. The procedure now is to remove a second link, given that link 1 is destroyed. This will produce the second link for the priority target list.

Table 3.27 demonstrates expected thruput reduction with a second link removed. Link 3 removal produces the greatest expected thruput reduction, and its subsequent destruction reduces total network thruput to zero. The priority target list consists of link 1 in the first position, followed by link 3.

Further refinement of this network model will not be attempted in our thesis. The example network problem developed thus far depicts a simplified problem in the interdiction planner's decision-making process. We use this small network to demonstrate supply thruput, thruput reduction, expected

Table 3.26

Table 3.23 with Five Aircraft Against Each Link

Removed Link	Reduction of Thruput by Link Removal (tons/hr)	Probability of Attack Success (*)	(**)	Expected Thruput Reduction (tons/hr)	Total Thruput Cost (dollars/hr
1	50	.7	.94	47	$1470.00
2	42	.6	.88	37	1830.00
3	50	.7	.94	47	1680.00
4	8	.8	.999	8	3150.00
5	50	.5	.82	41	1680.00
6	0	.8	.999	0	3510.00

*Probability of attack success before anti-air defense for each independent sortie.

**Probability of attack success with anti-air defense included.

Table 3.27

Expected Reduction of Thruput for Second Link Removal

Removed Link	Reduction of Thruput by Link Removal (tons/hr)	Probability of Attack Success	Expected Thruput Reduction (tons/hr)	Total Thruput Cost (dollars/hr)
2	0	.88	0	$1470.00
3	42	.94	39	0.00
4	0	.999	0	1470.00
5	32	.82	26	700.00
6	0	.999	0	1470.00

thruput reduction, priority target lists, probability of attack success with and without anti-air defenses, and network absorption. The purpose of Chapter III has been to acquaint the reader with all the above mentioned elements of the interdiction model, so that Chapter IV will be easier to understand. The basis for this study is to develop a computer program which rapidly calculates the above mentioned elements for an interdiction planner when networks become too large for simple calculation. Chapter IV demonstrates the use of this computer program to solve large network problems.

CHAPTER IV

COMPUTER SOLUTION OF AN EXAMPLE NETWORK

The example network developed in Chapter III depicts a simplified problem in the interdiction planner's decision process. Suppose the planner has a problem of planning interdiction strikes against a 28 link logistics network and sufficient resources are available to the planner to launch multiple sorties against multiple network targets. Such a problem is beyond the realm of simple hand calculations and requires computer assistance to develop an optimal solution. The optimal solution is based upon maximum reduction in supply thruput with the constraint that loss of aircraft and personnel be kept at acceptable levels. In order for the planner to solve this problem, the following questions must be answered successfully:

1. What is the estimated capacity of each link in the network?

2. What is the estimated cost to the enemy to move supplies along each link?

3. Considering general network absorption, what is the network supply thruput?

4. Which links are capacity-critical links?

5. Which critical links contain vulnerable targets?

6. Considering the nature of each target, the weapons delivery system, type weapons employed, anticipated target weather, and estimates of anti-air defense, what is the probability of attack success for each link?

7. How much will network defense absorption affect enemy supply thruput?

8. Using sensitivity analysis, what is the optimal number of sorties to send against a network?

9. Which links constitute the target priority list?

We have developed a computer program which will answer the above questions for the interdiction planner. In order to demonstrate the full capabilities of the computer program, the example network in Figure 4.1 will be processed. The example network was ran on the CREATE time sharing computer system at Wright-Patterson AFB, Ohio. However, the program can be used on any similar FORTRAN capable computer system. Our intent is to explain the input and output processes performed by a program user. A more technical user's guide for program operating details is included in Appendix A. In this chapter, we are concentrating on interpretation of the input and output data. All subsequent tables in this chapter reflect printout that appears in the computer terminal listing during program processing.

The example network contains 14 nodes and 28 links. Five of the links are two-way links and allow traffic in two directions when required. The remaining links are direction oriented from the source to the sink. It would have been

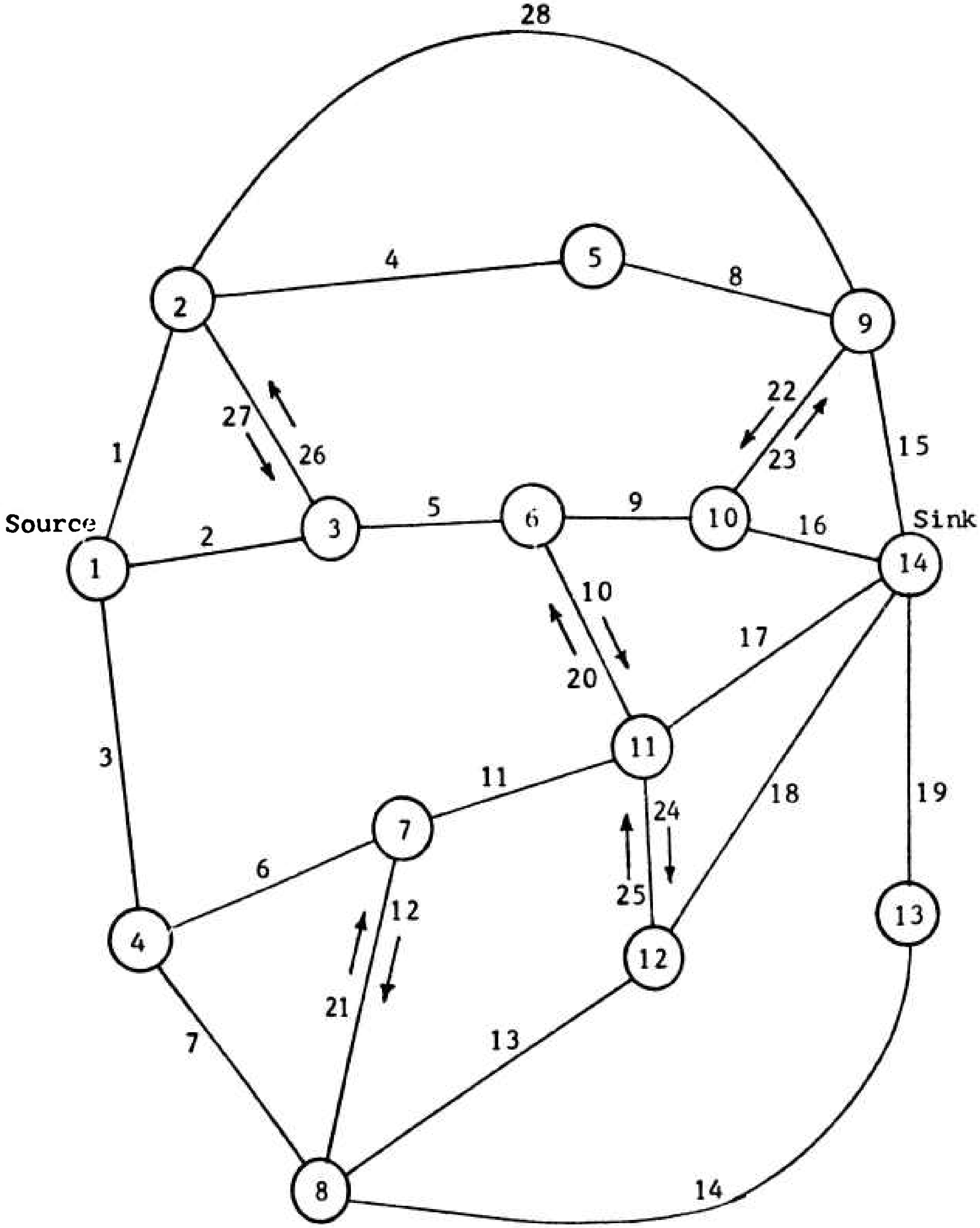

Figure 4.1

Example Network Model

possible to establish more two-way links for this problem and the computer program could have easily processed the expanded problem, but we decided that more could be demonstrated if the example problem were not too complex.

Initial data needed by the interdiction planner are estimated link capacities, general network absorption, and predicted cost to the network user for traversing each link. This data can be obtained from intelligence sources such as reconnaissance overflights, indigenous agents, or other personnel experienced in making accurate estimates.

Initially, the interdiction planner does not know which links are capacity-critical links. Therefore, the planner is not confident as to which links will most likely be defended should the enemy have a network defense capability. For this example, we assume that the enemy has sufficient resources and capability to defend critical targets in the network. Critical targets consist of those physical elements of the network whose destruction can close a link to supply thruput. Because the planner is not yet certain which links are critical links, each link is given an equal probability that an attacking aircraft can destroy that link. In this example, each link will be given an equal probability of attack success, 1.0.

The interdiction planner inserts the example network node and link numbers into the computer program, as shown in Table 4.1.

For the computer program to function properly, link numbering must begin at the integer base number of 1. Other

restrictions are that node 1 be the source node and that the highest numbered node be the sink node. Otherwise, the computer program will not be able to develop a "FROM-TO" matrix. The last line of Table 4.1 is a switch to signal end of link and node input.

TABLE 4.1

Input of Nodes and Links

```
CODES FOR PRINT OUT OF FEASIBLE ROUTES
          0=PRINT OUT NUMBER OF FEASIBLE ROUTES
          1=PRINT OUT NUMBER AND LIST FEASIBLE ROUTES

INPUT CODE FOR PRINT OUT OF FEASIBLE ROUTES
=1
INPUT FROM-NODE, TO-NODE, LINK NUMBER AT EACH =.
AFTER ALL LINKS HAVE BEEN ENTERED, ENTER 0,0,0 FOR NEXT =.
=1,2,1
=1,4,3
=1,3,2
=2,5,4
=3,6,5
=4,7,6
=4,8,7
=5,9,8
=6,10,9
=6,11,10
=7,11,11
=7,8,12
=8,12,13
=8,13,14
=9,14,15
=10,14,16
=11,14,17
=12,14,18
=13,14,19
=11,6,20
=8,7,21
=9,10,22
=10,9,23
=11,12,24
=12,11,25
=3,2,26
=2,3,27
=2,9,28
=0,0,0
```

The program asks for input of the number of network nodes in order to establish the correct size of the "FROM-TO" matrix, as shown in Table 4.2.

Table 4.2

FROM-TO Matrix

```
INPUT THE NUMBER OF NODES IN THE NETWORK
=14

FROM-TO MATRIX IS

  0  1  2  3  0  0  0  0  0  0  0  0  0  0

  0  0 27  0  4  0  0  0 28  0  0  0  0  0

  0 26  0  0  0  5  0  0  0  0  0  0  0  0

  0  0  0  0  0  0  6  7  0  0  0  0  0  0

  0  0  0  0  0  0  0  0  8  0  0  0  0  0

  0  0  0  0  0  0  0  0  0  9 10  0  0  0

  0  0  0  0  0  0  0 12  0  0 11  0  0  0

  0  0  0  0  0  0 21  0  0  0  0 13 14  0

  0  0  0  0  0  0  0  0  0 22  0  0  0 15

  0  0  0  0  0  0  0  0 23  0  0  0  0 16

  0  0  0  0  0 20  0  0  0  0  0 24  0 17

  0  0  0  0  0  0  0  0  0  0 25  0  0 18

  0  0  0  0  0  0  0  0  0  0  0  0  0 19

  0  0  0  0  0  0  0  0  0  0  0  0  0  0

CHECK THE FROM-TO MATRIX.
IS THE DATA INPUT PROPERLY?  (YES OR NO)
=YES
```

The computer will then print out the "FROM-TO" matrix for verification of correct data input. The rows of the

matrix, numbered from the source node at the top, represent the "FROM" nodes. The columns represent the "TO" nodes, with the highest numbered sink node in the last column on the right. From Table 4.2, we see that link 27 connects node 2 to node 3 as verified in the network in Figure 4.1. If link and node data are confirmed in the matrix, an affirmative reply allows the program to proceed. A negative reply will permit the planner to correct his inputs.

The computer program next asks for input of link capacities, general network absorption, link costs, and link destruction probabilities. The input data are shown in Table 4.3. In Table 4.3 , link capacities and network absorption are represented in tons per hour. Link cost is in terms of dollars per ton.

Table 4.3

Input of Link Characteristics

```
INPUT THE NUMBER OF LINKS IN THE NETWORK
=28
INPUT LINK CAPACITIES
=250,150,300,120,200,220,180,100,170,60,100,60,100,120,120
=300,100,170,150,60,60,60,60,30,30,40,40,40
INPUT CAPACITY REQUIRED FOR LINK SUPPORT
=1,1,1,3,2,2,2,3,2,3,2,2,3,3,1,1,1,1,1,3,2,2,2,2,2,1,1,3
INPUT LINK COST/DISTANCE
=5,2,2,4,8,10,5,4,4,7,6,8,7,6,7,16,8,12,13,2,4,8,6,8,2,2,3,15
INPUT LINK DESTRUCTION PROBABILITIES
=1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1
```

At this point, the program requests identification of the links leading to the sink. This allows the program to compute maximum flow of supplies reaching the sink. The

program then asks for the maximum number of air interdiction sorties that can be assigned to attack a target. Optimal assignment of aircraft sorties is not necessary at this time, so the number 1 is entered into the program. Additionally, anti-air defense is not of concern yet, so a zero is entered into the two questions concerned with anti-air defense. These five inputs are shown in Table 4.4.

Table 4.4

Input of Links Leading to Sink and Attack Sortie Data

```
HOW MANY LINKS LEAD TO SINK?
=5
INPUT LINKS LEADING TO SINK
=15,16,17,18,19
HOW MANY AIRCRAFT CAN BE ASSIGNED TO A TARGET?
=1
HOW MANY MISSILES LAUNCHED AT EACH AIRCRAFT?
=0
WHAT IS THE PROBABILITY OF A MISSILE HIT?
=0
```

The computer now prints out the number of feasible routes in the network and the routes themselves, if so desired. Usually, a printout of the feasible routes is not accomplished because they merely show which routes are available to the network user. The feasible routes are included in Table 4.5 to demonstrate how feasible routes would be printed. The number "34" to the right of the words "FEASIBLE ROUTES" is the total number of feasible routes in the network. Each row in Table 4.5 lists the link sequence that forms a feasible route. For example, the first feasible route in row

one starts at the source and proceeds via links 1, 28, and 15 to reach the sink. A look at Figure 4.1 verifies the feasible routes. The computer program prevents route looping or back-tracking by not allowing a feasible route sequence to pass through a particular node more than once. (Note that the maximum number of links in a feasible route is one less than the number of nodes in the network.)

Table 4.5

Feasible Routes

FEASIBLE ROUTES: 34

1 28 15

2 26 28 15

1 4 8 15

2 26 4 8 15

2 5 9 23 15

1 27 5 9 23 15

3 6 11 20 9 23 15

3 7 21 11 20 9 23 15

3 7 13 25 20 9 23 15

3 6 12 13 25 20 9 23 15

2 5 9 16

1 27 5 9 16

3 6 11 20 9 16

3 7 21 11 20 9 16

3 7 13 25 20 9 16

3 6 12 13 25 20 9 16

Table 4.5 (continued)

1	28	22	16		
2	26	28	22	16	
1	4	8	22	16	
2	26	4	8	22	16
2	5	10	17		
1	27	5	10	17	
3	6	11	17		
3	7	21	11	17	
3	7	13	25	17	
3	6	12	13	25	17
3	7	13	18		
3	6	12	13	18	
2	5	10	24	18	
1	27	5	10	24	18
3	6	11	24	18	
[illegible]	7	21	11	24	18
3	7	14	19		
3	6	12	14	19	

Printout of the next bit of data begins the return of significant information for the interdiction planner. Maximum thruput of supplies and its associated cost is provided. More importantly, final flow of tonnage through each link is reflected. Table 4.6 shows the final flow through each link, its original capacity, and a confirmation of the cost data entered earlier in the program. The total cost of $15,903.00

is obtained by multiplying final flow for each link by cost for each link and summing for all 28 links. Maxflow of 542 was obtained by summing final flow for links 15, 16, 17, 18, and 19, leading to the sink.

Table 4.6

Output of Network Flow and Cost

MAXFLOW = 542 TOTAL COST = 15903.00

LINK	FINAL FLOW	CAPACITY	COST
1	138	250	5.00
* 2	131	150	2.00
* 3	273	300	2.00
4	96	120	4.00
5	138	200	8.00
6	110	220	10.00
* 7	163	180	5.00
* 8	96	100	4.00
9	105	170	4.00
*10	57	60	7.00
11	67	100	6.00
*12	58	60	8.00
*13	90	100	7.00
*14	116	120	6.00
*15	119	120	7.00
16	117	300	16.00
*17	99	100	8.00
18	91	170	12.00
19	116	150	13.00
20	24	60	2.00
21	15	60	4.00
22	35	60	8.00
23	23	60	6.00
*24	28	30	8.00
*25	27	30	2.00
*26	32	40	2.00
*27	39	40	3.00
*28	35	40	15.00

All links with an asterisk are flowing at full capacity. Minor differences between final flow and capacity of these links is accounted for by general network absorption.

The first low cost route using a link provides network absorption tonnage. Subsequent uses of that link will not include absorption for the link but may include absorption for downstream links being used for the first time. Each of the asterisked links is a potential capacity-critical link. However, other links may also be candidates; such other links would be characterized by a high absolute level of supply thruput. Consequently, until link removal is performed on the network, identification of those links which provide greatest expected reduction in thruput is not an easy task. As link removal is performed in the next four tables, Tables 4.7, 4.8, 4.9, and 4.10, it is instructional to observe the changes in net reduction of thruput.

In Table 4.7, each of the 28 links is removed, one at a time, and net reduction in thruput is calculated for the 27 link-reduced network. For example, with link 3 removed from the network, the total reduction in supply thruput is 274 tons per hour. Expected reduction, as a decision-making tool, is to be disregarded at this time. It is used in the second run of the computer program when probability of attack success is calculated for each link. Notice the negative values for links 21, 23, 24, and 26 in Table 4.7. This means that actual network thruput is increased by the amount of the negative value when that link is removed. Thus, with link 26 removed, the amount of network thruput increases by 40 tons per hour. This occurs because lowest cost routes are assigned link flow before more costly routes. With link 26 removed, some other routes, which can handle more capacity, receive

link flow assignments. In effect, removal of link 26 allows the network user to thruput 40 more tons per hour of supply but at a higher overall cost. Cost jumps from $15,903.00 to $17,135.00 for total network thruput. This negative value phenomenon changes, as more links are removed from the network, in the same respect as positive values.*

Table 4.7

Reduced Flow Caused by Removal of Target Link

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	138	138.	11564.00
2	116	116.	11999.00
3	274	274.	7423.00
4	95	95.	13301.00
5	151	151.	10699.00
6	110	110.	11617.00
7	127	127.	12592.00
8	95	95.	13301.00
9	106	106.	11913.00
10	9	9.	15529.00
11	64	64.	13374.00
12	32	32.	14681.00
13	66	66.	13412.00
14	87	87.	13215.00
15	31	31.	15950.00
16	117	117.	11429.00
17	6	6.	15905.00
18	58	58.	13764.00
19	87	87.	13215.00
20	24	24.	14943.00
21	-2	-2.	15748.00
22	35	35.	14363.00
23	-2	-2.	15641.00
24	-2	-2.	16039.00
25	0	0.	15902.00
26	-40	-40.	17135.00
27	39	39.	14499.00
28	35	35.	14363.00

LINK 3 DESTROYED MAXFLOW = 268

*If the enemy is completely indifferent to any form of cost, we can operate the model with zero cost inputs, avoiding negative values at this point.

In Table 4.7, link 3 exhibits the greatest net reduction in supply thruput when it is removed from the network. Link 3 is, therefore, a capacity-critical link. The computer program identifies the capacity-critical link and simulates its destruction by removing it from the network. Removal of link 3 reduces maximum thruput to 268 tons per hour from the previous 542 tons per hour.

With removal of the first link completed, the computer program continues by removing a second link, given that the first link is removed, as shown in Table 4.8.

Removal of link 5 in Table 4.8 produces the greatest net reduction of thruput. Those links with zero net reduction reflect the earlier removal of link 3. Maximum supply thruput is reduced to 130 tons per hour with links 5 and 3 removed.

Tables 4.9 and 4.10 show removal of a third and fourth link, respectively. The third capacity-critical link is link 1, while link 26 is the fourth capacity-critical link. With this fourth link removed, network thruput is reduced to zero. This can be verified by referring back to Figure 4.1 where we see that destruction of links 3, 5, and 1, and 26 prevents supply flow from source to sink. The computer program stops when network thruput has been reduced to zero.

At this point, the interdiction planner knows which links are capacity-critical to the enemy in terms of greatest net reduction thruput. However, it is not clear if these four links can be successfully attacked. More information is needed; the following questions must be answered:

Table 4.8

Removal of the Second Link

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	137	137.	3169.00
2	105	105.	4048.00
3	0	0.	0.
4	95	95.	4821.00
5	138	138.	2993.00
6	0	0.	7423.00
7	0	0.	7423.00
8	95	95.	4821.00
9	82	82.	4393.00
10	-4	-4.	7823.00
11	0	0.	7423.00
12	0	0.	7423.00
13	0	0.	7423.00
14	0	0.	7423.00
15	31	31.	7470.00
16	93	93.	3909.00
17	-4	-4.	7823.00
18	0	0.	7423.00
19	0	0.	7423.00
20	0	0.	7423.00
21	0	0.	7423.00
22	35	35.	5883.00
23	-2	-2.	7161.00
24	0	0.	7423.00
25	0	0.	7423.00
26	-40	-40.	8655.00
27	39	39.	6019.00
28	35	35.	5883.00

LINK 5 DESTROYED MAXFLOW = 130

Table 4.9

Removal of the Third Link

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	98	98.	608.00
2	0	0.	3025.00
3	0	0.	0.
4	94	94.	937.00
5	0	0.	0.
6	0	0.	2993.00
7	0	0.	2993.00
8	94	94.	937.00
9	0	0.	2993.00
10	0	0.	2993.00
11	0	0.	2993.00
12	0	0.	2993.00
13	0	0.	2993.00
14	0	0.	2993.00
15	73	73.	2079.00
16	11	11.	2509.00
17	0	0.	2993.00
18	0	0.	2993.00
19	0	0.	2993.00
20	0	0.	2993.00
21	0	0.	2993.00
22	11	11.	2509.00
23	0	0.	2993.00
24	0	0.	2993.00
25	0	0.	2993.00
26	0	0.	3025.00
27	0	0.	2993.00
28	34	34.	1888.00

LINK 1 DESTROYED MAXFLOW = 32

Table 4.10

Removal of the Fourth Link

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	0	0.	0.
2	32	32.	0.
3	0	0.	0.
4	-3	-3.	910.00
5	0	0.	0.
6	0	0.	608.00
7	0	0.	608.00
8	-3	-3.	910.00
9	0	0.	608.00
10	0	0.	608.00
11	0	0.	608.00
12	0	0.	608.00
13	0	0.	608.00
14	0	0.	608.00
15	2	2.	1080.00
16	0	0.	608.00
17	0	0.	608.00
18	0	0.	608.00
19	0	0.	608.00
20	0	0.	608.00
21	0	0.	608.00
22	0	0.	608.00
23	0	0.	608.00
24	0	0.	608.00
25	0	0.	608.00
26	32	32.	0.
27	0	0.	608.00
28	0	0.	608.00

LINK 26 DESTROYED MAXFLOW = 0

* * NETWORK THRUPUT HAS BEEN STOPPED * *

1. Which network links contain vulnerable targets?

2. What is the physical nature of each target?

3. What is the probability of attack success against each link?

4. What is the enemy's capability to defend the network?

Information about network vulnerable targets would come from photographs and maps collected by intelligence agencies. Further, enlarged photographs would provide information about the physical nature of each target. Appropriate weapons and weapons delivery systems are selected, based upon the type target in each link. With the addition of anticipated target area weather, the interdiction planner is ready to assign probability of attack success for every network link. The interdiction planner accomplishes this for every link, not just capacity-critical links, because he is not yet confident that capacity-critical links can be attacked without relatively heavy losses of aircraft and aircrews. The enemy's capability to defend the network, combined with the nature of a target, may cause realignment of capacity-critical links. The second computer run will reveal this information.

After completing assignment of probability of attack success against the links, the interdiction planner adjusts network thruput absorption by including network defense absorption. This estimate is based on the type and quantity of anti-air defense weapons the enemy has to defend the network, including an estimate of the enemy's policy with regard to expending fire power. This information allows an estimate

of the number of AAA rounds, or missiles, that could be fired at each attacking aircraft. An estimate is also needed for the probability that an anti-aircraft round (missile) will hit an aircraft.

The interdiction planner is now ready for the second run of the computer program. Table 4.11 shows the changes to input data for the second run. Capacity required for link support now contains network defense absorption and general network absorption. Link destruction probabilities now reflect an accurate estimate of probability of attack success for each network link. This time, the interdiction planner can enter into the computer program the number of aircraft that will be assigned to one target. This allows sensitiv analysis concerning optimal allocation of aircraft. The final change to input data reflects the enemy's anti-air defense capability. Remaining input data are the same as before.

Table 4.11

Revised Input Data

```
INPUT CAPACITY REQUIRED FOR LINK SUPPORT
=10,8,10,4,10,8,8,4,5,3,3,3,4,4,5,4,5,4,4,2,2,2,2,2,2,8,8,2

INPUT LINK DESTRUCTION PROBABILITIES
=.2,.3,.2,.6,.2,.4,.4,.6,.5,.7,.7,.7,.6,.6,.5
=.6,.5,.6,.6,.8,.9,.8.,9.,8.,8,.4,.4,.8

HOW MANY AIRCRAFT CAN BE ASSIGNED TO A TARGET?
=5
HOW MANY MISSILES LAUNCHED AT EACH AIRCRAFT?
=200
WHAT IS THE PROBABILITY OF A MISSILE HIT?
=.001
```

Table 4.12 shows the maximum network thruput and total cost for the second run. Maximum flow of network thruput and total cost are lower, due to the inclusion of arbitrary network defense absorption. Comparison of Table 4.12 with Table 4.6 demonstrates how network defense absorption affects each link.

Table 4.12

Network Flow and Total Cost for Second Run

MAXFLOW = 476 TOTAL COST = 13818.00

LINK	FINAL FLOW	CAPACITY	COST
1	136	250	5.00
2	101	150	2.00
3	239	300	2.00
4	91	120	4.00
5	110	200	8[illegible]
6	91	220	10.[illegible]
7	148	180	5.00
8	91	100	4.00
9	63	170	4.00
10	57	60	7.00
11	49	100	6.00
12	57	60	8.00
13	80	100	7.00
14	110	120	6.00
15	115	120	7.00
16	75	300	16.00
17	95	100	8.00
18	81	170	12.00
19	110	150	13.00
20	10	60	2.00
21	15	60	4.00
22	36	60	8.00
23	24	60	6.00
24	24	30	8.00
25	23	30	2.00
26	19	40	2.00
27	28	40	3.00
28	36	40	15.00

The computer program next determines final capacity-critical network links by using link removal until supply thruput drops to zero. The program first performs link removal with one aircraft attacking each target. Then, the program performs link removal again with two aircraft attacking each target. This will continue until link removal is performed, with five aircraft attacking one target. (Five was the number of attacking aircraft specified in the input data of Table 4.11.) The difference in link removal, with these five different quantities of attacking aircraft, is based on the change to probability of attack success and is revealed in expected reduction of thruput. Recall that we discussed in Chapter III the effect on probability of attack success by changes in number of aircraft and enemy anti-air defenses. Our program computes the expected reduction of thruput, using the following formula:

$$\begin{array}{l}\text{Expected} \\ \text{reduction of} \\ \text{thruput}\end{array} = ((1 - (1\text{-PROB}(1\text{-P})^{NM})^{NS})\text{x}\left(\begin{array}{l}\text{net reduction} \\ \text{of thruput*}\end{array}\right)$$

where "PROB" equals input link destruction probability; "P" equals input probability of a hit by a missile or AAA round; "NM" equals number of missiles or rounds fired at an aircraft; "NS" equals number of aircraft attacking the target. Comparison of expected reduction in thruput for each of the five different quantities of attacking aircraft enables the interdiction planner to select an optimum number of aircraft to

*This is the thruput reduction if, in fact, the link has been cut.

send against a target. The planner must weigh the consequences of overuse of limited aircraft resources against expected gains from target destruction.

Link removal, with one aircraft attacking one target, is shown in Table 4.13. (Table 4.13 extends for five pages, due to its length.) Capacity-critical links are links 8, 3, 2, 28, and 27 in that order. This means that a target priority list can be established, using that particular order of link destruction if only one aircraft is available to attack a target.

Table 4.13

Link Removal for One Attacking Aircraft

TARGET LINK ATTACKED BY 1 AIRCRAFT
EACH AIRCRAFT ENCOUNTERS 200 MISSILE

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	136	22.	9707.00
2	95	23.	10598.00
3	244	40.	6371.00
4	94	46.	11181.00
5	112	18.	9935.00
6	91	30.	10283.00
7	102	33.	11348.00
8	94	46.	11181.00
9	67	27.	11148.00
10	-5	-2.	14029.00
11	42	24.	12196.00
12	17	10.	13195.00
13	43	21.	12148.00
14	61	30.	12-63.00
15	27	11.	13935.00
16	75	37.	10796.00
17	-12	-4.	14527.00
18	31	15.	12681.00
19	61	30.	12063.00
20	10	7.	13418.00
21	-2	-1.	13690.00
22	36	24.	12234.00
23	-2	-1.	13566.00
24	-2	-1.	13950.00
25	-2	-1.	13841.00
26	-40	-13.	15061.00
27	32	10.	12650.00
28	36	24.	12234.00

LINK 8 DESTROYED MAXFLOW = 382

Table 4.13 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	36	6.	9996.00
2	93	23.	8493.00
3	240	39.	3897.00
4	0	0.	11181.00
5	115	19.	7714.00
6	87	28.	7809.00
7	102	33.	8711.00
8	0	0.	0.
9	63	26.	9213.00
10	-5	-2.	11408.00
11	38	22.	9722.00
12	17	10.	10558.00
13	43	21.	9512.00
14	61	30.	9430.00
15	-45	-18.	13373.00
16	5	2.	10981.00
17	-12	-4.	11906.00
18	31	15.	10044.00
19	61	30.	9430.00
20	6	4.	10944.00
21	-6	-4.	11213.00
22	0	0.	11181.00
23	-2	-1.	11455.00
24	-2	-1.	11313.00
25	-2	-1.	11245.00
26	-40	-13.	12446.00
27	28	9.	10212.00
28	-2	-1.	11420.00

LINK 3 DESTROYED MAXFLOW = 142

Table 4.13 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	40	7.	2625.00
2	95	23.	1325.00
3	0	0.	0.
4	0	0.	3897.00
5	109	18.	866.00
6	0	0.	3897.00
7	0	0.	3897.00
8	0	0.	0.
9	57	23.	2166.00
10	-4	-2.	4274.00
11	0	0.	3897.00
12	0	0.	3897.00
13	0	0.	3897.00
14	0	0.	3897.00
15	-41	-16.	5926.00
16	0	0.	3897.00
17	-4	-1.	4274.00
18	0	0.	3897.00
19	0	0.	3897.00
20	0	0.	3897.00
21	0	0.	3897.00
22	0	0.	3897.00
23	2	1.	4008.00
24	0	0.	3897.00
25	0	0.	3897.00
26	-36	-11.	4999.00
27	32	10.	2841.00
28	2	1.	3973.00

LINK 2 DESTROYED MAXFLOW = 47

Table 4.13 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	47	8.	0.
2	0	0.	0.
3	0	0.	0.
4	0	0.	1325.00
5	14	2.	891.00
6	0	0.	1325.00
7	0	0.	1325.00
8	0	0.	0.
9	0	0.	1325.00
10	-1	0.	1386.00
11	0	0.	1325.00
12	0	0.	1325.00
13	0	0.	1325.00
14	0	0.	1325.00
15	1	0.	1842.00
16	0	0.	1325.00
17	-1	0.	1386.00
18	0	0.	1325.00
19	0	0.	1325.00
20	0	0.	1325.00
21	0	0.	1325.00
22	0	0.	1325.00
23	0	0.	1325.00
24	0	0.	1325.00
25	0	0.	1325.00
26	0	0.	1325.00
27	14	5.	891.00
28	33	22.	434.00

LINK 28 DESTROYED MAXFLOW = 14

Table 4.13 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	14	2.	0.
2	0	0.	0.
3	0	0.	0.
4	0	0.	434.00
5	14	2.	0.
6	0	0.	434.00
7	0	0.	434.00
8	0	0.	0.
9	0	0.	434.00
10	4	2.	330.00
11	0	0.	434.00
12	0	0.	434.00
13	0	0.	434.00
14	0	0.	434.00
15	0	0.	434.00
16	0	0.	434.00
17	4	2.	330.00
18	0	0.	434.00
19	0	0.	434.00
20	0	0.	434.00
21	0	0.	434.00
22	0	0.	434.00
23	0	0.	434.00
24	0	0.	434.00
25	0	0.	434.00
26	0	0.	434.00
27	14	5.	0.
28	0	0.	0.

LINK 27 DESTROYED MAXFLOW = 0

* * NETWORK THRUPUT HAS BEEN STOPPED * *

Link removal, with two aircraft attacking a target, is shown in Table 4.14. Notice the change in capacity-critical links. Now link 3 should be attacked first, followed by links 8, 2, 28, and 27. This change occurs because the probability of attack success with two aircraft attacking a target produces a realignment of probability factors used to convert net reduction to expected reduction.

Table 4.14

Link Removal for Two Attacking Aircraft

TARGET LINK ATTACKED BY 2 AIRCRAFT
EACH AIRCRAFT ENCOUNTERS 200 MISSILE

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	136	41.	9707.00
2	95	41.	10598.00
3	244	73.	6371.00
4	94	70.	11181.00
5	112	34.	9935.00
6	91	50.	10283.00
7	102	56.	11348.00
8	94	70.	11181.00
9	67	44.	11148.00
10	-5	-4.	14029.00
11	42	34.	12196.00
12	17	14.	13195.00
13	43	32.	12148.00
14	61	45.	12063.00
15	27	18.	13935.00
16	75	56.	10796.00
17	-12	-7.	14527.00
18	31	23.	12681.00
19	61	45.	12063.00
20	10	9.	13418.00
21	-2	-1.	13690.00
22	36	32.	12234.00
23	-2	-1.	13566.00
24	-2	-1.	13950.00
25	-2	-1.	13841.00
26	-40	-21.	15061.00
27	32	18.	12650.00
28	36	32.	12234.00

LINK 3 DESTROYED MAXFLOW = 232

Table 4.14 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	136	41.	2336.00
2	95	41.	3254.00
3	0	0.	0.
4	90	67.	3897.00
5	109	33.	2801.00
6	0	0.	6371.00
7	0	0.	6371.00
8	90	67.	3897.00
9	57	37.	4101.00
10	-8	-6.	6895.00
11	0	0.	6371.00
12	0	0.	6371.00
13	0	0.	6371.00
14	0	0.	6371.00
15	27	18.	6488.00
16	65	48.	3749.00
17	-3	-5.	6895.00
18	0	0.	6371.00
19	0	0.	6371.00
20	0	0.	6371.00
21	0	0.	6371.00
22	36	32.	4787.00
23	-2	-1.	6119.00
24	0	0.	6371.00
25	0	0.	6371.00
26	-40	-21.	7614.00
27	32	18.	5187.00
28	36	32.	4787.00

LINK 8 DESTROYED MAXFLOW = 142

Table 4.14 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	40	12.	2625.00
2	95	41.	1325.00
3	0	0.	0.
4	0	0.	3897.00
5	109	33.	866.00
6	0	0.	3897.00
7	0	0.	3897.00
8	0	0.	0.
9	57	37.	2166.00
10	-4	-3.	4274.00
11	0	0.	3897.00
12	0	0.	3897.00
13	0	0.	3897.00
14	0	0.	3897.00
15	-41	-26.	5926.00
16	0	0.	3897.00
17	-4	-2.	4274.00
18	0	0.	3897.00
19	0	0.	3897.00
20	0	0.	3897.00
21	0	0.	3897.00
22	0	0.	3897.00
23	2	2.	4008.00
24	0	0.	3897.00
25	0	0.	3897.00
26	-36	-19.	4999.00
27	32	18.	2841.00
28	2	2.	3973.00

LINK 2 DESTROYED MAXFLOW = 47

Table 4.14 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	47	14.	0.
2	0	0.	0.
3	0	0.	0.
4	0	0.	1325.00
5	14	4.	891.00
6	0	0.	1325.00
7	0	0.	1325.00
8	0	0.	0.
9	0	0.	1325.00
10	-1	0.	1386.00
11	0	0.	1325.00
12	0	0.	1325.00
13	0	0.	1325.00
14	0	0.	1325.00
15	1	1.	1842.00
16	0	0.	1325.00
17	-1	0.	1386.00
18	0	0.	1325.00
19	0	0.	1325.00
20	0	0.	1325.00
21	0	0.	1325.00
22	0	0.	1325.00
23	0	0.	1325.00
24	0	0.	1325.00
25	0	0.	1325.00
26	0	0.	1325.00
27	14	8.	891.00
28	33	29.	434.00

LINK 28 DESTROYED MAXFLOW = 14

Table 4.14 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	14	4.	0.
2	0	0.	0.
3	0	0.	0.
4	0	0.	434.00
5	14	4.	0.
6	0	0.	434.00
7	0	0.	434.00
8	0	0.	0.
9	0	0.	434.00
10	4	3.	330.00
11	0	0.	434.00
12	0	0.	434.00
13	0	0.	434.00
14	0	0.	434.00
15	0	0.	434.00
16	0	0.	434.00
17	4	3.	330.00
18	0	0.	434.00
19	0	0.	434.00
20	0	0.	434.00
21	0	0.	434.00
22	0	0.	434.00
23	0	0.	434.00
24	0	0.	434.00
25	0	0.	434.00
26	0	0.	434.00
27	14	8.	0.
28	0	0.	0.

LINK 27 DESTROYED MAXFLOW = 0

* * NETWORK THRUPUT HAS BEEN STOPPED * *

It is instructional to note the overall increase in expected reduction for Table 4.14 as opposed to Table 4.13. Expected reduction will continue to increase as more aircraft are assigned to a target. A priority target list, with two aircraft attacking a target, consists of links 3, 8, 2, 28, and 27, in that order.

Link removal for three and four aircraft attacking a target is not shown, to avoid redundancy. Both situations produce the same priority target list. The only change from previous link removal is a greater expected reduction in thruput. In fact, link removal, with five aircraft attacking a target, produces no change in priority target list from link removal with two aircraft attacking a target. This final situation is shown in Table 4.15. As can be seen, expected reduction is equal to net reduction in some cases. One interesting point is the expected reduction caused by removing the second link, given that the first link (link 3) is destroyed. Links 4 and 8 tie for greatest expected reduction in thruput and also tie with total thruput cost. In this case, the computer program arbitrarily selects the highest numbered link, link 8. If the interdiction planner had reason to destroy link 4 instead of link 8, he would be free to do so.* Referring to Figure 4.1, note that destroying link 4 instead of link 8 does not affect the subsequent selection of other capacity-critical links. In other network configurations, selecting an alternate capacity-critical link may affect selection of subsequent capacity-critical links. The interdiction planner can overcome the problem of links tied for greatest expected reduction of thruput and total thruput cost by making a slight adjustment in probability of attack success for these links and rerunning the computer program.

*For example, link 4 might be closer to his base of operation.

Table 4.15

Link Removal for Five Attacking Aircraft

TARGET LINK ATTACKED BY 5 AIRCRAFT
EACH AIRCRAFT ENCOUNTERS 200 MISSILE

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	136	80.	9707.00
2	95	72.	10598.00
3	244	144.	6371.00
4	94	91.	11181.00
5	112	66.	9935.00
6	91	78.	10283.00
7	102	88.	11348.00
8	94	91.	11181.00
9	67	62.	11148.00
10	-5	-4.	14029.00
11	42	41.	12196.00
12	17	17.	13195.00
13	43	42.	12148.00
14	61	59.	12063.00
15	27	25.	13935.00
16	75	72.	10796.00
17	-12	-11.	14527.00
18	31	30.	12681.00
19	61	59.	12063.00
20	10	10.	13418.00
21	-2	-1.	13690.00
22	36	36.	12234.00
23	-2	-1.	13566.00
24	-2	-1.	13950.00
25	-2	-1.	13841.00
26	-40	-34.	15061.00
27	32	28.	12650.00
28	36	36.	12234.00

LINK 3 DESTROYED MAXFLOW = 232

Table 4.15 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	136	80.	2336.00
2	95	72.	3254.00
3	C	0.	0.
4	90	87.	3897.00
5	109	64.	2801.00
6	0	0.	6371.00
7	0	0.	6371.00
8	90	87.	3897.00
9	57	53.	4104.00
10	-8	-7.	6895.00
11	0	0.	6371.00
12	0	0.	6371.00
13	0	0.	6371.00
14	0	0.	6371.00
15	27	25.	6488.00
16	65	63.	3749.00
17	-8	-7.	6895.00
18	0	0.	6371.00
19	0	0.	6371.00
20	0	0.	6371.00
21	0	0.	6371.00
22	36	36.	4787.00
23	-2	-1.	6119.00
24	0	0.	6371.00
25	0	0.	6371.00
26	-40	-34.	7614.00
27	32	28.	5187.00
28	36	36.	4787.00

LINK 8 DESTROYED MAXFLOW = 142

Table 4.15 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	40	24.	2625.00
2	95	72.	1325.00
3	0	0.	0.
4	0	0.	3897.00
5	109	64.	866.00
6	0	0.	3897.00
7	0	0.	3897.00
8	0	0.	0.
9	57	53.	2166.00
10	-4	-3.	4274.00
11	0	0.	3897.00
12	0	0.	3897.00
13	0	0.	3897.00
14	0	0.	3897.00
15	-41	-38.	5926.00
16	0	0.	3897.00
17	-4	-3.	4274.00
18	0	0.	3897.00
19	0	0.	3897.00
20	0	0.	3897.00
21	0	0.	3897.00
22	0	0.	3897.00
23	2	2.	4008.00
24	0	0.	3897.00
25	0	0.	3897.00
26	-36	-31.	4999.00
27	32	28.	2841.00
28	2	2.	3973.00

LINK 2 DESTROYED MAXFLOW = 47

Table 4.15 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	47	28.	0.
2	0	0.	0.
3	0	0.	0.
4	0	0.	1325.00
5	14	8.	891.00
6	0	0.	1325.00
7	0	0.	1325.00
8	0	0.	0.
9	0	0.	1325.00
10	-1	0.	1386.00
11	0	0.	1325.00
12	0	0.	1325.00
13	0	0.	1325.00
14	0	0.	1325.00
15	1	1.	1842.00
16	0	0.	1325.00
17	-1	0.	1386.00
18	0	0.	1325.00
19	0	0.	1325.00
20	0	0.	1325.00
21	0	0.	1325.00
22	0	0.	1325.00
23	0	0.	1325.00
24	0	0.	1325.00
25	0	0.	1325.00
26	0	0.	1325.00
27	14	12.	891.00
28	33	33.	434.00

LINK 28 DESTROYED MAXFLOW = 14

Table 4.15 (continued)

TARGET LINK	NET REDUCTION	EXPECTED REDUCTION	TOTAL THRUPUT COST
1	14	8.	0.
2	0	0.	0.
3	0	0.	0.
4	0	0.	434.00
5	14	8.	0.
6	0	0.	434.00
7	0	0.	434.00
8	0	0.	0.
9	0	0.	434.00
10	4	4.	330.00
11	0	0.	434.00
12	0	0.	434.00
13	0	0.	434.00
14	0	0.	434.00
15	0	0.	434.00
16	0	0.	434.00
17	4	4.	330.00
18	0	0.	434.00
19	0	0.	434.00
20	0	0.	434.00
21	0	0.	434.00
22	0	0.	434.00
23	0	0.	434.00
24	0	0.	434.00
25	0	0.	434.00
26	0	0.	434.00
27	14	12.	0.
28	0	0.	0.

LINK 27 DESTROYED MAXFLOW = 0

* * NETWORK THRUPUT HAS BEEN STOPPED * *

With a selection of the optimal number of aircraft to attack a target, the final target priority list can be established. The interdiction planner's problem has been solved. Each of the nine questions posed at the beginning of this chapter has been answered.

CHAPTER V

SUMMARY AND CONCLUSION

Summary

In a tactical warfare environment, the commander of friendly forces has a major problem in determining the most effective use of available aircraft sorties. Aircraft can be launched in different roles, such as air superiority, air interdiction, and close air support missions. The different roles compete for available aircraft resources so that complete satisfaction can rarely be attained for each type mission due to limited aircraft resources. The commander needs a method to determine potential results of sortie application in each of the air roles. The objective of this thesis is to provide a method for determining potential results in one of the air roles, air interdiction of a capacitated network.

We have constructed a network model which contains key variables relative to two functions: network supply thruput and air interdiction. The model is converted to a computer language, FORTRAN, for rapid calculation of model variables to aid interdiction planners. Hand calculation of model variables for a very simple network is demonstrated in Chapter III. However, simple networks are rarely the concern

of interdiction planners. Large networks, such as the example network in Chapter IV, present a far greater problem because interaction among model variables is difficult to perceive.

The computer program is based on a simple algorithm for determining thruput in small capacitated networks. The basic algorithm, which enables hand calculation of feasible routes, supply thruput, and total network cost, is converted to FORTRAN and expanded to include network absorption and priority target list construction for an air interdiction planner.

Conclusion

In Chapter II, two general questions about air interdiction effectiveness were posed and served as the basis for our study. These two questions were:

1. Whether or not a capacitated transportation network can be interdicted to reduce flow capacity below enemy supply requirements;

2. Whether or not available aircraft have a satisfactory probability of attack success.

We found that there exists a practical method which enables an air interdiction planner to answer these two questions. The method is our FORTRAN based computer program which accomplishes the repetitious and tedious steps of determining feasible routes, network thruput (absorption included), total network cost, and capacity-critical links. The program allows the quick construction of a priority target list based on probability of attack success, expected

reduction in thruput, and optimal allocation of available attack aircraft. By using our program, an interdiction planner is able to determine the effect of air interdiction on a capacitated transportation network and, furthermore, whether or not interdiction aircraft have a satisfactory probability of attack success.

A reproduced copy of our FORTRAN program is located in Appendix A. Also included in Appendix A is a user's guide we developed for computer processing of capacitated transportation network problems.

Areas for Further Research

While our FORTRAN program accomplishes the task of solving anti-capacity interdiction problems, we found that other forms of interdiction problems can be analyzed by computer simulation. We have included in Appendix B an anti-goods interdiction model, which demonstrates that computer simulation can be useful in addressing transportation network problems. The benefit of computer simulation is that additional variable aspects of the overall interdiction problem may be included in the network model. For instance, a model could be developed to combine anti-capacity interdiction strategy with anti-goods interdiction strategy.

The use of computer simulation as a method for solving interdiction problems should be further investigated. We suggest including additional, realistic variables to better analyze the network problem. Examples of variables, which should be included in the network model, are: link repair

time, damaged links, and mixed modes of travel. Link repair time and damaged links have previously been discussed. The expression, mixed modes of travel, refers to changing modes of travel and a loading/unloading operation. For example, trains can haul supplies along some links in the network, then offload supplies to trucks which haul the supplies along other network links to the sink node. Including this variable provides an option for interdiction aircraft to attack node targets in addition to link targets.

The importance of further research into the overall interdiction environment cannot be overstressed. Additional analytical methods must be developed to provide further insight into the large number of variables associated with air interdiction. Interaction among all the variables in the environment is difficult to perceive. Improper application of air power can be the result. Eventually, analytical methods will be necessary to determine the interaction among variables associated with each role within tactical warfare. We foresee tactical warfare as a major component of United States military policy through the 1980's. Limited aircraft resources will prevent widespread deployment of permanent overseas forces. A highly-mobile, highly-effective tactical force will be required to respond to worldwide challenges. The effectiveness of this tactical force will be based on skillful application of air power. Without analytical assistance, decision-makers may find it impossible to correctly apply aircraft resources.

APPENDIX A

FORTRAN ANTI-CAPACITY INTERDICTION PROGRAM

In this appendix we have included a user's guide, a description listing of the program variables, and a listing of our FORTRAN interdiction computer program. There is a smaller version of this program, which does not include the interdiction feature, available at the School of Systems and Logistics (AFIT), Wright-Patterson AFB, Ohio. The small version calculates feasible routes in a network, network thruput, and cost of the total thruput.

Program Variables

Variable Name	Description
NO	Code for print out of feasible routes
I	Row or column index
J	Row or column index
MM	Link identifier input and maximum feasible route index
ITOFR(I,J)	"FROM-TO" matrix
IPTOFR(I,J)	Permanent "FROM-TO" matrix
K	Number of nodes in the network
ANS	Input indicator for an incorrect "FROM-TO" matrix
IN	Number of links in the network

Preceding page blank

ICAPIN(I)	Link capacities
ISORB(I)	Capacity used by network absorption elements
COSTIN(I)	Link cost or distance
PROB(I)	Link probabilities of one aircraft destroying non-defended link
LS	Number of links leading to the sink
LSINK(I)	Identification of links leading to the sink
NA	Maximum number of aircraft that can be assigned to one target
NM	Number of missiles (or rounds) fired at each aircraft
P	Probability that a missile (or round) will hit an aircraft
L	Row or column index
IFRUT(I,L)	Array of feasible routes
TOTCOST	Total network cost
LINKUSE(I)	Amount of link flow under network maxflow conditions
MAXFLOW	Total network thruput reaching the sink
MAX	Network thruput before interdiction
NS	Number of sorties attacking a target
LI	Row or column index
INFRNOD(LI)	"FROM" nodes corresponding to links selected for feasible route
IRUT(L)	Working vector of links during formulation of feasible routes
IL	Row or column index
KI	Row or column index
LINK(I)	Vector of links that are flowing
IMIN	Holds last value during minimum or maximum search

IHOLD	Holds matrix element during minimum or maximum search
IRUTCAP(I,J)	Array of link capacities on feasible routes
RUTCOST(I,J)	Array of link costs on feasible routes
SUMCOST(I)	Vector of summed cost of each feasible route
LCOSTRUT(I)	Low cost route or routes in case of ties
COSTLOW	Cost of low cost route or routes
ISUM	Network absorption applied to a link (its own plus any downstream, non-flowing links in the feasible route)
ISMCAP(I)	Smallest capacity link in a feasible route
ILGSMCAP	Largest of competing small capacity links
IRTE	Feasible route selected for flow
IA	Temporarily destroyed link while determining reduced flow
IB	Row index for searching destroyed link in "FROM-TO" matrix
JB	Column index for searching destroyed link in "FROM-TO" matrix
RMCOST(IA)	Network cost with link destroyed
MREDFLOW	Maximum flow for network with link destroyed
NETREDUC(IA)	Net reduction in flow with link destroyed
EXPREDUC(IA)	Expected reduction in flow with link destroyed
BIGEXP	Largest expected reduction which designates the link picked for permanent destruction

USER'S GUIDE

We dimensioned the computer program for networks with not more than fifteen nodes, thirty-five links, five links leading to the sink, and a maximum of one hundred eighty-five calculated feasible routes. The network size capability of the computer program is only limited by available computer core.

To prepare the network input data, identify each network node with a positive integer, using 1 for the source node and numbering consecutively, with the largest number assigned to the sink node. The links may be numbered in any order, providing the integers start with 1 and continue sequentially to the last link. Two-way links should be treated as two separate links, each with an identifying number (one "northbound," the other "southbound"). Each link can then be described by a start or "FROM" node number and an ending or "TO" node number associated with a link number. This is the same as the "FROM-TO" matrix element identification in the thruput algorithm.

On a time-sharing computer terminal, call the program and give the RUN command. A code listing for feasible route output will be printed, and then you will be asked to input the code for print out of feasible routes. If you only want to know how many feasible routes are in the network and not the listing of each route, enter a code of Ø. If, instead, you want a complete listing of all the routes, enter a code

of 1. The next instruction will ask you to input a FROM-NODE, TO-NODE, and LINK NUMBER at each = sign. For example, if link 3 goes from node 1 to node 2, your first entry would be =1,2,3 and then press the RETURN key. Continue to enter link information at each = sign until all links have been entered. Enter Ø,Ø,Ø at the = sign, following the last link entry to signify the end of the link input data. Next, you will be asked to input the number of nodes in the network. This number should correspond to the highest numbered node, the sink node. The program then prints out the "FROM-TO" matrix. You will then be asked to check the "FROM-TO" matrix for errors and answer "YES" or "NO" as to proper data input. Each link number should be located in a row corresponding to the "FROM" node number and a column corresponding to the "TO" node number. Also, the matrix should have the same number of rows and columns as nodes. If matrix data and size are correct, answer "YES"; otherwise, answer "NO." When the answer is "NO," the program branches back and instructs you to correct the input data. If a link number is in the wrong element position, it must be removed by entering the row and column numbers and a Ø for the link number. Then, enter the correct link input data. For example, if link 5 were associated with nodes 5 and 7, instead of nodes 4 and 7, the correction would be: = 5,6,Ø

= 4,7,5

= Ø,Ø,Ø

The entry of Ø,Ø,Ø follows the last correction entry. If the error were the matrix size rather than individual elements,

the number of nodes input is incorrect. In this case, when you are asked to correct the matrix values, enter Ø,Ø,Ø and you will then be asked to input the number of nodes which will correct the matrix size. When the "FROM-TO" matrix is correct and you confirm its correctness by answering "YES," you will be asked to input the number of links in the network. The number of links should correspond to the highest link number. The next input will be link capacities. Capacities may be entered on one line starting with link 1 consecutively to the highest number link. If the capacities require more than one line, DO NOT place a comma after the last entry of a line. A comma causes the next link capacity to be Ø. A line entry should be as follows:

= 7Ø, 8Ø, 6Ø, 1ØØ, 9Ø

The next three input requests are entered in the same manner as the link capacities. Capacity required for link support is requested after the link capacities. The next entry is link cost in dollars per ton, dollars per ton-mile, miles, hundreds of miles, or whatever cost element desired. The link destruction probability requested is the probability that a single aircraft, on one attack, can successfully destroy an undefended link. The caution, "DO NOT place a comma after the last entry on a line," applies to link capacities, link support, link cost, and link destruction probabilities. Next, the number of links that terminate at the sink node is requested, followed by a call for input of the identification numbers of the links leading to the sink. To determine the best use of aircraft sorties, the remaining

input data is the maximum number of aircraft that can be assigned to one target, the number of missiles (or rounds) that might be fired at each aircraft, and the probability that a missile (or round) will hit an aircraft.

As previously described, data input errors in the "FROM-TO" matrix can be corrected before the program continues. Also, procedure errors for capacity and cost data input have been identified. Some uncorrected typing errors may be detected before program completion. If another = sign appears after inputing link capacities or cost, the number input for the number of links may be greater than the total links in the network. If this is the case and all other data are correct, then input Ø's for capacities and costs, after the last link data, to fill the requested links. This will cause additional output for nonexistent links that have Ø values. However, the remainder of output should be correct if all other input data were correct. Other errors can be detected by examining the output.

The output will indicate the number of feasible routes in the network, along with a route listing, if requested by code 1. A maxflow of thruput will be listed, along with the total cost of network thruput. Each link will be listed with its final flow and the capacity and cost that was input for the link.

If the program hesitates after printing feasible routes, check the value that was input for the number of links. If this number is less than the largest link number in the "FROM-TO" matrix, the program will not continue and

must be interrupted with the interrupt switch and rerun with proper data. If the number of feasible routes computed is greater than the dimension size, the output data for flow will be erroneous. Current dimension size is for 185 feasible routes. Check the output listing for erroneous link capacity and cost which would be caused by an error in the input data. If link capacity and cost are correct, then maxflow should equal the sum of flows for the links leading to the sink. An erroneous maxflow is caused by an error in the input data for links leading to the sink.

```
C  ***ANTI-CAPACITY INTERDICTION PROGRAM***
CHARACTER ANS
COMMON ICAPIN(35),MAXFLOW,TOTCOST,K,J,MM,L,I,IN,LS,NM,NS
COMMON RMCOST(35),NETREDUC(35),EXPREDUC(35),IPTOFR(15,15)
COMMON P,LI,RUTCOST(185,15),SUMCOST(185),LCOSTPUT(185)
COMMON IRUTCAP(185,15),ISMCAP(185),LINKUSE(35),LSINK(5)
C  DIMENSION IFRUT IN ACCORDANCE WITH MAX FEASIBLE ROUTES
COMMON IFRUT(185,15),IRUT(15),IFPNOD(15),COSTIN(35)
C  DIMENSION ITOFR IN ACCORDANCE WITH MAX NO. OF NODES
COMMON ITOFR(15,15),ISORR(35),PROB(35),LINK(185)
PRINT:"CODES FOR PRINT OUT OF FEASIBLE ROUTES"
PRINT:"           0=PRINT OUT NUMBER OF FEASIBLE ROUTES"
PRINT:"           1=PRINT OUT NUMBER AND LIST FEASIBLE",
&" ROUTES"
PRINT:"    "
PRINT:"INPUT CODE FOR PRINT OUT OF FEASIBLE ROUTES"
READ: NO
PRINT:"INPUT FROM-NODE, TO-NODE, LINK NUMBER  AT EACH =."
PRINT:"AFTER ALL LINKS HAVE BEEN ENTERED, ENTER 0,0,0",
&" FOR NEXT =."
GO TO 2
1 PRINT:"CORRECT THE FROM-TO MATRIX, PLACE 0 IN",
&" INCORRECT VALUE POSITION AND INPUT PROPER VALUE",
&" IN CORRECT POSITION"
2 DO 3 L=1,225
READ:I,J,MM
IF(I.EQ.0)GO TO 4
ITOFR(I,J)=MM
3 CONTINUE
4 PRINT:"INPUT THE NUMBER OF NODES IN THE NETWORK"
READ:K
PRINT:"  "
PRINT:"FROM-TO MATRIX IS"
DO 5 I=1,K
PRINT 100,(ITOFR(I,J),J=1,K)
100 FORMAT( /1X,23I3)
5 CONTINUE
PRINT:"  "
PRINT:"CHECK THE FROM-TO MATRIX."
PRINT:"IS THE DATA INPUT PROPERLY? (YES OR NO)"
READ:ANS
IF(ANS.EQ."NO")GO TO 1
DO 7 I=1,K
DO 6 J=1,K
IPTOFR(I,J)=ITOFR(I,J)
6 CONTINUE
7 CONTINUE
MM=1
CALL ROUTE ($8)
PRINT:"SUBSCRIPT FOR MAX LINKS USED IN FEASIBLE ROUTE",
&" HAS BEEN EXCEEDED, CHECK INPUT DATA AND",
&" DIMENSION SIZE BEFORE RERUN"
GO TO 19
8 PRINT:"INPUT THE NUMBER OF LINKS IN THE NETWORK"
```

```
READ:IN
PRINT:"INPUT LINK CAPACITIES"
READ:(ICAPIN(I),I=1,IN)
PRINT:"INPUT CAPACITY REQUIRED FOR LINK SUPPORT"
READ:(ISORB(I),I=1,IN)
PRINT:"INPUT LINK COST/DISTANCE"
READ:(COSTIN(I),I=1,IN)
PRINT:"INPUT LINK DESTRUCTION PROBABILITIES"
READ:(PROB(I),I=1,IN)
PRINT:"HOW MANY LINKS LEAD TO SINK?"
READ:LS
PRINT:"INPUT LINKS LEADING TO SINK"
READ:(LSINK(I),I=1,LS)
PRINT:"HOW MANY AIRCRAFT CAN BE ASSIGNED TO A TARGET?"
READ:NA
PRINT:"HOW MANY MISSILES LAUNCHED AT EACH AIRCRAFT?"
READ:NM
PRINT:"WHAT IS THE PROBABILITY OF A MISSILE HIT?"
READ:P
PRINT:"  "
PRINT:"  "
PRINT:"FEASIBLE ROUTES:",MM
IF(NO.NE.1)GO TO 12
DO 11 I=1,MM
DO 9 L=1,K
IF(IFRUT(I,L).EQ.0)GO TO 10
9 CONTINUE
10 NO=L-1
PRINT 100,(IFRUT(I,L),L=1,NO)
11 CONTINUE
12 CALL THRUPUT
TOTCOST=0.
DO 13 I=1,IN
TOTCOST=TOTCOST+COSTIN(I)*LINKUSE(I)
13 CONTINUE
MAXFLOW=0
DO 14 I=1,LS
MAXFLOW=MAXFLOW+LINKUSE(LSINK(I))
14 CONTINUE
MAX=MAXFLOW
PRINT 150,MAXFLOW,TOTCOST
150 FORMAT( //11X,"MAXFLOW =",I6,11X,"TOTAL COST =",
&F10.2)
PRINT 200
200 FORMAT( //17X,"LINK",3X,"FINAL FLOW",3X,"CAPACITY",
&4X,"COST")
DO 15 I=1,IN
PRINT 250,I,LINKUSE(I),ICAPIN(I),COSTIN(I)
250 FORMAT(18X,I2,8X,I3,8X,I3,5X,F6.2)
15 CONTINUE
IF(NA.EQ.0)GO TO 19
DO 18 NS=1,NA
PRINT 300
300 FORMAT( //1X,18("   *"))
```

```
PRINT 350,NS
350 FORMAT(19X,"TARGET LINK ATTACKED BY",I4,2X,
&"AIRCRAFT")
PRINT 400,NM
400 FORMAT(18X,"EACH AIRCRAFT ENCOUNTERS",I4,2X,
&"MISSILE",///)
DO 17 I=1,K
DO 16 J=1,K
ITOFR(I,J)=IPTOFR(I,J)
16 CONTINUE
17 CONTINUE
MAXFLOW=MAX
CALL LINKOUT
IF(I.EQ.9999)GO TO 19
18 CONTINUE
19 STOP
END
```

```
SUBROUTINE ROUTE (*)
COMMON ICAPIN(35),MAXFLOW,TOTCOST,K,J,MM,L,I,IN,LS,NM,NS
COMMON RMCOST(35),NETREDUC(35),EXPREDUC(35),IPTOFR(15,15)
COMMON P,LI,RUTCOST(185,15),SUMCOST(185),LCOSTRUT(185)
COMMON IRUTCAP(185,15),ISMCAP(185),LINKUSE(35),LSINK(5)
C  DIMENSION IFRUT IN ACCORDANCE WITH MAX FEASIBLE ROUTES
COMMON IFRUT(185,15),IRUT(15),IFRNOD(15),COSTIN(35)
C  DIMENSION ITOFR IN ACCORDANCE WITH MAX NO. OF NODES
COMMON ITOFR(15,15),ISORB(35),PROB(35),LINK(185)
DO 2 I=1,MM
DO 1 J=1,K
IFRUT(I,J)=0
1 CONTINUE
2 CONTINUE
J=K
MM=0
L=K+1
DO 3 I=1,K
IF(ITOFR(I,J).EQ.0)GO TO 3
GO TO 7
3 CONTINUE
C ***SEARCH FROM-TO MATRIX GOING RIGHT TO LEFT****
4 DO 6 I=1,K
IF(ITOFR(I,J).EQ.0)GO TO 6
DO 5 LI=L,K
IF(I.EQ.IFRNOD(LI))GO TO 6
5 CONTINUE
GO TO 7
6 CONTINUE
GO TO 9
7 L=L-1
IF(L.EQ.0)RETURN
IFRNOD(L)=I
```

```
IRUT(L)=ITOFR(I,J)
IF(I.EQ.1)GO TO 12
J=I
GO TO 4
C ***LOCATE LINKS ON BACKTRACK, SEARCH BY ROW***
8 L=L+1
IF(L.GT.K)RETURN1
9 DO 11 I=1,K
DO 10 J=1,K
IF(ITOFR(I,J).EQ.IRUT(L))GO TO 14
10 CONTINUE
11 CONTINUE
PRINT:"ERROR IF YOU REACH THIS"
RETURN
C ***COPY FEASIBLE ROUTE FOR SAVE***
12 LI=K-L+1
IL=L-1
MM=MM+1
DO 13 KI=1,LI
IL=IL+1
IFRUT(MM,KI)=IRUT(IL)
13 CONTINUE
C ***SEARCH COLUMN FOR MULTIPLE ENTRIES***
14 KI=I+1
DO 16 I=KI,K
IF(ITOFR(I,J).EQ.0)GO TO 16
DO 15 LI=L,K
IF(I.EQ.IFRNOD(LI))GO TO 16
15 CONTINUE
GO TO 17
16 CONTINUE
C ***NO MULTIPLE LINKS, BACKTRACK TO NEXT LINK***
GO TO 8
C ***FOUND FEASIBLE MULTIPLE LINK***
17 IRUT(L)=ITOFR(I,J)
IFRNOD(L)=I
J=I
GO TO 4
END


SUBROUTINE THRUPUT
COMMON ICAPIN(35),MAXFLOW,TOTCOST,K,J,MM,L,I,IN,LS,NM,NS
COMMON RMCOST(35),NETREDUC(35),EXPREDUC(35),IPTOFR(15,15)
COMMON P,LI,RUTCOST(185,15),SUMCOST(185),LCOSTRUT(185)
COMMON IRUTCAP(185,15),ISMCAP(185),LINKUSE(35),LSINK(5)
C  DIMENSION IFRUT IN ACCORDANCE WITH MAX FEASIBLE ROUTES
COMMON IFRUT(185,15),IRUT(15),IFRNOD(15),COSTIN(35)
C  DIMENSION ITOFR IN ACCORDANCE WITH MAX NO. OF NODES
COMMON ITOFR(15,15),ISORB(35),PROB(35),LINK(185)
DO 1 I=1,IN
LINK(I)=0
```

```
LINKUSE(I)=0
1 CONTINUE
IMIN=0
DO 3 I=1,MM
DO 2 J=1,K
IHOLD=IFRUT(I,J)
IMIN=MAX0(IMIN,IHOLD)
2 CONTINUE
3 CONTINUE
IF(IMIN.EQ.0)RETURN
DO 6 I=1,MM
DO 5 J=1,K
IF(IFRUT(I,J).EQ.0)GO TO 4
IRUTCAP(I,J)=ICAPIN(IFRUT(I,J))
GO TO 5
4 IRUTCAP(I,J)=9999
5 CONTINUE
6 CONTINUE
DO 9 I=1,MM
DO 8 J=1,K
IF(IFRUT(I,J).EQ.0)GO TO 7
RUTCOST(I,J)=COSTIN(IFRUT(I,J))
GO TO 8
7 RUTCOST(I,J)=0.
8 CONTINUE
9 CONTINUE
IMIN=0
10 DO 12 I=1,MM
SUMCOST(I)=0.
DO 11 J=1,K
SUMCOST(I)=SUMCOST(I)+RUTCOST(I,J)
11 CONTINUE
12 CONTINUE
DO 13 I=1,MM
IF(SUMCOST(I).LT.9999.)GO TO 14
13 CONTINUE
RETURN
14 COSTLOW=9999.
DO 15 I=1,MM
IF(LCOSTRUT(I).LT.0)GO TO 15
COSTLOW=AMIN1(COSTLOW,SUMCOST(I))
15 CONTINUE
DO 16 I=1,MM
IF(LCOSTRUT(I).LT.0)GO TO 16
LCOSTRUT(I)=0
IF(COSTLOW.NE.SUMCOST(I))GO TO 16
LCOSTRUT(I)=I
16 CONTINUE
DO 20 I=1,MM
IF(LCOSTRUT(I).LT.1)GO TO 20
ISUM=0
DO 19 J=1,K
IF(IFRUT(I,K-J+1).EQ.0)GO TO 19
IF(LINK(IFRUT(I,K-J+1)).GT.0)GO TO 17
```

```
ISUM=ISUM+ISORB(IFRUT(I,K-J+1))
17 IRUTCAP(I,K-J+1)=IRUTCAP(I,K-J+1)-ISUM
IF(IRUTCAP(I,K-J+1))18,18,19
18 LCOSTRUT(I)= -11
19 CONTINUE
20 CONTINUE
DO 21 I=1,MM
IF(LCOSTRUT(I).GT.0)GO TO 22
21 CONTINUE
IMIN=IMIN+1
IF(IMIN.GT.MM)RETURN
GO TO 10
22 DO 24 I=1,MM
IMIN=9999
DO 23 J=1,K
IHOLD=IRUTCAP(I,J)
IMIN=MIN0(IMIN,IHOLD)
23 CONTINUE
ISMCAP(I)=IMIN
24 CONTINUE
ILGSMCAP=0
DO 25 I=1,MM
IF(LCOSTRUT(I).LT.1)GO TO 25
ILGSMCAP=MAX0(ILGSMCAP,ISMCAP(I))
25 CONTINUE
DO 26 I=1,MM
IF(LCOSTRUT(I).LT.1)GO TO 26
IF(ISMCAP(I).EQ.ILGSMCAP)IRTE=I
26 CONTINUE
I=IRTE
DO 29 L=1,MM
IF(LCOSTRUT(L).EQ.I)GO TO 29
IF(LCOSTRUT(L).EQ.0)GO TO 29
LCOSTRUT(L)=0
ISUM=0
DO 28 J=1,K
IF(IFRUT(L,K-J+1).EQ.0)GO TO 28
IF(LINK(IFRUT(L,K-J+1)).GT.0)GO TO 27
ISUM=ISUM+ISORB(IFRUT(L,K-J+1))
27 IRUTCAP(L,K-J+1)=IRUTCAP(L,K-J+1)+ISUM
28 CONTINUE
29 CONTINUE
DO 30 J=1,K
IF(IFRUT(I,J).EQ.0)GO TO 30
LINK(IFRUT(I,J))=I
LINKUSE(IFRUT(I,J))=LINKUSE(IFRUT(I,J))+ISMCAP(I)
IRUTCAP(I,J)=IRUTCAP(I,J)-ISMCAP(I)
30 CONTINUE
DO 34 L=1,MM
DO 33 LI=1,K
IF(IFRUT(L,LI).EQ.0)GO TO 33
DO 31 J=1,K
IF(IFRUT(L,LI).EQ.IFRUT(I,J))IRUTCAP(L,LI)=IRUTCAP(I,J)
31 CONTINUE
```

```
IF(IRUTCAP(L,LI))32,32,33
32 RUTCOST(L,LI)=9999.
33 CONTINUE
34 CONTINUE
IMIN=0
GO TO 10
END



SUBROUTINE LINKOUT
COMMON ICAPIN(35),MAXFLOW,TOTCOST,K,J,MM,L,I,IN,LS,NM,NS
COMMON RMCOST(35),NETREDUC(35),EXPREDUC(35),IPTOFR(15,15)
COMMON P,LI,RUTCOST(185,15),SUMCOST(185),LCOSTRUT(185)
COMMON IRUTCAP(185,15),ISMCAP(185),LINKUSE(35),LSINK(5)
C  DIMENSION IFRUT IN ACCORDANCE WITH MAX FEASIBLE ROUTES
COMMON IFRUT(185,15),IPUT(15),IFRNOD(15),COSTIN(35)
C  DIMENSION ITOFR IN ACCORDANCE WITH MAX NO. OF NODES
COMMON ITOFR(15,15),ISORB(35),PROB(35),LINK(185)
1 DO 8 IA=1,IN
DO 3 IB=1,K
DO 2 JB=1,K
IF(ITOFR(IB,JB).EQ.IA)GO TO 4
2 CONTINUE
3 CONTINUE
GO TO 8
4 ITOFR(IB,JB)=0
CALL ROUTE ($5)
PRINT:"SUBSCRIPT FOR MAX LINKS USED IN FEASIBLE ROUTE",
&" HAS BEEN EXCEEDED, CHECK INPUT DATA AND",
&" DIMENSION SIZE BEFORE RERUN"
I=9999
RETURN
5 CALL THRUPUT
TOTCOST=0.
DO 6 I=1,IN
TOTCOST=TOTCOST+COSTIN(I)*LINKUSE(I)
6 CONTINUE
RMCOST(IA)=TOTCOST
MREDFLOW=0
DO 7 I=1,LS
MREDFLOW=MREDFLOW+LINKUSE(LSINK(I))
7 CONTINUE
NETREDUC(IA)=MAXFLOW-MREDFLOW
EXPREDUC(IA)=(1-(1-PROB(IA)*(1-P)**NM)**NS)*NETREDUC(IA)
ITOFR(IB,JB)=IA
8 CONTINUE
BIGEXP=0.
DO 9 I=1,IN
R=EXPREDUC(I)
T=AINT(R)
R=EXPREDUC(I)-T
EXPREDUC(I)=T
```

```
IF(R.GT.0.4999)EXPREDUC(I)=EXPREDUC(I)+1.
BIGEXP=AMAX1(BIGEXP,EXPREDUC(I))
9 CONTINUE
IF(BIGEXP.LT.1.)GO TO 18
DO 10 I=1,IN
LCOSTRUT(I)=0
IF(BIGEXP.EQ.EXPREDUC(I))LCOSTRUT(I)=I
10 CONTINUE
BIGEXP=99999.
DO 11 I=1,IN
IF(LCOSTRUT(I).EQ.0)GO TO 11
BIGEXP=AMIN1(BIGEXP,RMCOST(I))
11 CONTINUE
DO 12 I=1,IN
IF(LCOSTRUT(I).EQ.0)GO TO 12
IF(BIGEXP.EQ.RMCOST(I))L=I
12 CONTINUE
PRINT 450
450 FORMAT( /16X,"TARGET",6X,"NET",6X,"EXPECTED",3X,
&"TOTAL THRUPUT")
PRINT 500
500 FORMAT(17X,"LINK",4X,"REDUCTION",2X,"REDUCTION",7X,
&"COST")
DO 13 I=1,IN
PRINT 550,I,NETREDUC(I),EXPREDUC(I),RMCOST(I)
550 FORMAT(18X,I2,8X,I3,6X,F5.0,5X,F10.2)
13 CONTINUE
MAXFLOW=MAXFLOW-NETREDUC(L)
DO 14 I=1,IN
RMCOST(I)=0.
NETREDUC(I)=0
EXPREDUC(I)=0.
14 CONTINUE
DO 16 I=1,K
DO 15 J=1,K
IF (ITOFR(I,J).EQ.L)GO TO 17
15 CONTINUE
16 CONTINUE
17 ITOFR(I,J)=0
PRINT 600,L,MAXFLOW
600 FORMAT( ///12X,"LINK",I4,2X,"DESTROYED",17X,
&"MAXFLOW =",I6)
GO TO 1
18 PRINT 650
650 FORMAT( /16X,"* *   NETWORK THRUPUT HAS BEEN",
&" STOPPED   * *")
RETURN
END
```

APPENDIX B

GASP IIB INTERDICTION SIMULATION PROGRAM

Computer Simulation

The network model constructed in this thesis does not contain every key variable which impacts upon real-world interdiction situations. We readily admit this deficiency because it is inherent in model building. We constructed a model which is just one part of the overall problem of air interdiction operation. As pointed out in Chapter I (7), the basic idea of network modeling is to separate a large problem into smaller component parts and then analyze the parts. Yet, by separating a large problem into smaller components, certain consequences result. The large problem may be altered when translating it into smaller components. Interaction among variables may be changed from their original relationships, or may inadvertently be disregarded. Finally, important data may be lost. The effect of these consequences can be lessened by converting a network model to computer simulation. Computer simulation allows an analyst to attack the original large problem without reducing it to smaller components, provided the analyst is aware of the variables of the large problem and their interaction. As one author states,

Preceding page blank

"Simulation offers the most flexible and realistic representation for complex problems of any quantitative techniques" (16:256).

We believe our FORTRAN based program is a valuable tool for assisting interdiction planners; however, the omission of some variables, due to lack of research time, limits the program. If repair time of destroyed links were included in the model, link restrike information would be available. Also, if the concept of damaged links were included, the interdiction planner could more realistically calculate network thruput. The addition of these and other variables to our FORTRAN based program may not be feasible. Our computer program has reached the capacity limits of computer core space allowed for compilation and execution of programs using the CREATE time sharing system available at the Air Force Institute of Technology School of Systems and Logistics at Wright-Patterson AFB, Ohio. Our program contains more than 400 lines of coding and requires considerable core space for processing program variables. While additional core space can be obtained from the central processing site upon request, the addition of more variables may eventually exceed routine core space allocation. In other words, the program can only be run after special procedures are enacted at the central site.

Considering the above arguments, we decided to investigate the feasibility of using GASP IIB (13), a computer simulation language, to simulate the network interdiction problem. GASP IIB solves the problem of core space allocation

because it uses the "batch-world" of CREATE where larger amounts of core space are routinely available for processing a program. Consequently, more variables may be included in a model. Due to the limited time available for additional research, the model we simulated contains a relatively simple network. Our main objective is demonstrating that a capacitated network interdiction model can be successfully simulated.

The arbitrary model variables used in the simulation are as follows:

1. A transportation network with a source node, a sink node, and one link. The link has the following physical characteristics:

TYPE LINK - - - - - Unimproved roadway

LENGTH- - - - - - - 75 miles

CAPACITY- - - - - - 50 tons per hour (intelligence estimate)

ROAD SURFACE- - - - Dirt

TOPOGRAPHY- - - - - Hilly; heavily tree covered

2. Trucks. We assumed that two different sized trucks are available to network users. Two-ton trucks comprise 70 percent of the total number of trucks; one-ton trucks, 30 percent. We also assumed that the network user has sufficient trucks to maintain a steady flow of supplies flowing along the link. Trucks have two missions. One is to carry supply thruput and the other is to carry network defense support for anti-air defense sites and general network support for truck operations. Other trucks using the roadway are

discounted, as are empty trucks returning to the source for additional supplies.

3. Supply thruput. A cumulative total of supply thruput, in terms of tons per hour, is accumulated. The total varies depending upon network absorption, the number of supply trucks destroyed, and traffic discipline (as truck interval is increased, fewer supplies will flow over a given period of time).

4. Network absorption. Absorption is divided into two types:

a. General network absorption indicates the amount of supply thruput (gasoline, oil, parts, etc.) consumed by each truck that traverses the network length.

b. Network defense absorption indicates the reduction in supply thruput caused by AAA support trucks interspersing among and maintaining traffic discipline with thruput supply trucks.

5. Aircraft. Not every aircraft in the simulation model is an air interdiction aircraft. Some aircraft are performing other missions, such as observation or air superiority; but they are vulnerable to AAA fire from network defenders if passing within firing range. These other aircraft do not strike interdiction targets. We assumed that air interdiction aircraft are available 24 hours a day to strike targets. Because of the limited time available to perform this additional simulation, we have limited the investigation to an analysis of thruput as it is affected

by certain components of network absorption. Therefore, AAA is considered as a function of opposing aircraft entering the target area and all aircraft entering the area can potentially draw AAA fire. Since interdiction aircraft attacking trucks can alter the steady-state flow of support material (general network absorption and network defense absorption), the results of truck attack are the only interdiction efforts accounted for in the simulation. The attack by other aircraft is considered only for the amount of AAA fire they draw.

6. Anti-air defenses. The simulation assumes that only 37mm and 57mm anti-air defense weapons are available to network defenders. These AAA sites are assumed to fire at maximum firing rate whenever an opposing force aircraft passes within range. Destruction of AAA sites by air interdiction aircraft is not considered.

Scenario

Supply trucks, fully loaded with supplies, enter the simulation environment (hereafter referred to as "the system") at the source node. Their departure down the road is controlled by a ground transportation officer who regulates traffic discipline. The ground transportation officer determines proper truck interval based on road conditions, truck speed, and threat of aircraft attack. Time intervals between truck entries are constant for a simulation run: 5 minutes for runs 1 and 2, then reduced 2.5 minutes for runs 3 and 4.

Traffic discipline must be maintained by truck drivers in order to avoid traffic bottlenecks along the route

and to make less appealing targets for interdiction aircraft. For this simulation, we assumed that truck drivers are briefed to drive 30 mph for the entire 75 miles. Due to steep grades and chuck holes, the average speed varies from the desired. Due to the large number of trucks involved, the spread of enroute times about the mean is assumed to be normally distributed, with a mean time of 150 minutes and a standard deviation of 2 minutes. An arbitrary upper and lower limit is set at 160 and 140 minutes, respectively. If trucks enter the system every five minutes, more than 8,000 trucks are involved in the simulation time period of 28 days.

Supply truck departure interval from the source node is interrupted only by support truck departure. Support trucks do not have a regular departure time; they are specifically ordered. If none are ordered, only supply trucks depart from the source node. When a support truck is ordered, it departs from the source node 30 minutes later. Regular intervals for supply trucks are resumed after the support truck departs from the source node.

General network absorption is also assumed to be a constant for the simulation. One-ton trucks arbitrarily consume 100 pounds of gasoline, oil, and other supplies while traversing the link; two-ton trucks consume 150 pounds enroute. This type absorption applies to supply trucks and support trucks. We assume sufficient general network supplies are on hand at the start of the simulation and two more tons are ordered at the sink each time two tons are consumed.

At the beginning of simulation, we assume that AAA sites have sufficient resources on hand to defend the network. AAA sites are resupplied when two tons of their supplies are consumed. For example, when two tons of AAA rounds have been expended, an order is placed for two tons of rounds to be delivered to the sink node. We assumed distribution of support to AAA sites takes place from the sink node. Delivery of AAA support to the sink node is by one two-ton truck or two one-ton trucks. For ease of support requirements determination, we assume that two pounds of AAA support are expended every time an AAA site fires one round.

Aircraft arrive over the transportation link at the average rate of one every 30 minutes. This is an arbitrary rate established for comparison of effects relative to an arrival rate of one every 15 minutes. One percent of the aircraft arriving over the link remains outside the range of AAA fire. Of the remaining 99 percent, 8 percent are within the range of AAA fire long enough to draw from zero to fifty rounds of fire. This 8 percent of aircraft are not interdiction aircraft but other aircraft, such as observation aircraft. Thus, 91 percent of aircraft arriving over the link are air interdiction aircraft. Air interdiction aircraft can make up to three attack passes at trucks before departing the network and are within the range of AAA fire long enough to draw fire. Data concerning the number of rounds fired at attacking and non-attacking aircraft are assumed to be normally distributed, with a mean of 75 and a standard deviation of 13. This assumption is based on the large number of aircraft

being fired at by AAA sites. Upper and lower bounds for AAA rounds being fired are arbitrarily assigned for our simulation at 125 and 25 rounds respectively.

As mentioned above, air interdiction aircraft can make up to three passes at trucks on the link. The associated probability of an interdiction aircraft, making attack passes, is shown in Table B.1.

Table B.1

Probability for Number of Passes

Number of Passes	Probability (pass)
0	.08
1	.31
2	.46
3	.15

Again, we arbitrarily assigned the number of possible passes with associated probabilities. In a practical application of an actual problem, historical data would be used to form the attack pass parameters. The number of possible passes and probabilities depends on target location, target type, aircraft type, aircraft configuration regarding ordnance and fuel, and anti-air defense systems.

Each interdiction aircraft is given a probability of .01 of detecting a lone truck along the tree-canopied road. If more trucks are on the road, an attacking aircraft has an

increased probability of sighting a suitable target, according to the following formula:

$$\text{Probability (detection)} = 1 - (1-.01)^N$$

where "N" represents the number of trucks on the road. For example, if 60 trucks are on the 75 mile link, the probability of an interdiction aircraft detecting at least one truck is

$$\text{Probability (detection)} = 1 - (1-.01)^{60} = .453.^*$$

From this, it can be seen that the fewer trucks on the road, the smaller probability each aircraft has of detecting a truck. A battle of strategies develops whereby the network ground transportation officer must weigh the consequences of increased truck detection against demands to thruput more supplies. On the other side of the coin, the air interdiction decision-maker must weigh the consequences of increased cost, for an increased sortie rate, against the possibility of non-detection of trucks. It may be costly, in terms of opportunity lost, to expend aircraft operating time on a relatively small number of trucks.

Given that an attacking aircraft detects a truck, the arbitrarily assigned probability of truck destruction is as shown in Table B.2. Clearly, if an aircraft cannot make a strike pass, the probability of truck destruction is zero. The remaining probabilities are based on release of

---

*We assume, further, that the pilot can determine the truck's direction of travel and attacks only targets heading towards the sink (i.e., full trucks).

ordnance by attacking aircraft. For example, if an aircraft releases all its iron bombs (smart bombs and strafing passes are not considered) on one pass, the probability of truck destruction is .40. If iron bombs are released in two passes, fewer bombs are dropped on each single pass, hence the probability of .25 per pass. This same concept applies to three passes.

Table B.2

Probability of Truck Destruction Per Pass

Number of Passes	P (destruction)
0	.00
1	.40
2	.25 (per pass)
3	.15 (per pass)

If a truck is destroyed, it is removed from the system. Before removal, the truck is checked to determine type and tonnage. If it is a support truck, a like-sized replacement support truck is ordered to enter the system in 30 minutes. If a supply truck is destroyed, another replacement truck is not ordered, due to the continuous nature of supply truck generation. The simulation does not address the subject of aircraft destruction. We are more interested in the aspect of network thruput reduction as a result of truck destruction and network absorption.

Approach

Four computer runs have been made, each run simulating 28 days of activity. The first run assumes that trucks depart from the source node at five minute intervals and aircraft arrive over the link at the rate of one every 30 minutes. The second run determines the effect on the model when aircraft arrive over the link at the rate of one every 15 minutes. Truck departure interval is the same as for the first run. For the third computer run, aircraft arrivals are set back to one every 30 minutes; but truck departure interval from the source node is changed to 2.5 minutes. This latter change has the effect of doubling the number of trucks on the road in a time period. The fourth computer run determines the effect on the model when truck departure interval is 2.5 minutes and aircraft arrival rate is one aircraft every 15 minutes.

Each computer run is divided into four separate time periods of one week each. This is accomplished to obtain the benefit of four separate random number seeds for a computer run. It is possible for one random number seed to bias the results of a simulation run. This can occur from the combination of a particular random number seed with a computer's pseudo random number generator. A bad number for a random number seed may produce random numbers that occur so often as to establish an unwanted pattern; for example, number sequences are produced which are not random within the scenario.

To obtain more reliable statistics from a simulation run, the system being modeled should be operating in a steady-state condition. To overcome initial conditions when the system is empty and to allow the system to stabilize, statistics are not collected until 240 minutes after the start of simulation. Statistics are then collected for the next 10,080 minutes to represent seven days of activity.

Results

Table B.3 shows a summary of simulation results for the four different combinations of truck intervals and aircraft arrival times. Maintaining a given truck interval, while increasing aircraft arrival rate, does not significantly change the total system flow. Reducing truck departure interval from 5 minutes to 2.5 minutes approximately doubles the tons per hour of flow reaching the sink node. Decreasing aircraft arrival interval from 30 to 15 minutes approximately doubles the number of aircraft entering the system and, consequently, approximately doubles AAA firing. Increased aircraft arrivals, with a given truck interval, approximately doubles the number of trucks destroyed. Also, with a given truck interval and increased AAA firings, the percentage of flow absorbed by AAA doubles. The proportion of flow absorbed by general support remains almost constant, at slightly less than 4 percent for all four simulation runs.

Analysis of Results

To analyze the results of the simulation, the following topics will be discussed:

Table B.3

Simulation Results

	Time Between Arrivals*			
	Run 1 T= 5 min A= 30 min	Run 2 T= 5 min A= 15 min	Run 3 T=2.5 min A= 30 min	Run 4 T=2.5 min A= 15 min
Average Total System Flow Per Hour (tons)	20.97	20.76	41.92	41.31
Average Network Absorption Per Hour (tons)	1.07	1.31	1.89	2.13
Average Thruput Flow Per Hour (tons)	19.90	19.45	40.03	39.18
Percent Absorption by General Network Support	3.99	3.99	3.98	3.98
Percent Absorption by Network Defense (AAA)	1.19	2.41	0.59	1.21
Number of Truck Entries (four weeks)	8552	8673	16985	17103
Trucks Destroyed (four weeks)	171	370	308	623
Number of Aircraft Entries (four weeks) (99% - all arrivals)	1321	2645	1317	2642
Air Interdiction Aircraft (91% - all arrivals)	1215	2433	1212	2431
Number of AAA Firings (four weeks)	2311	4610	2283	4615

*Interval times for trucks are represented by "T=" and aircraft by "A=."

1. The effect of more aircraft entering the system;

2. The effect of more trucks entering the system;

3. How network thruput was affected by truck destruction and network absorption.

The result of an increased aircraft arrival rate over the link is an increase in the number of aircraft that have a given probability of truck detection. This produces increased truck detection and, subsequently, increased truck destruction. In the first computer run, trucks depart the source node at 5 minute intervals, driving an average speed of 30 mph. Since it takes each truck an average of 150 minutes to traverse the link, an average of 30 trucks are on the road during steady-state conditions. The probability of truck detection with 30 trucks on the link is

$$\text{Probability (detection)} = 1 - (1-.01)^{30} = .26$$

Therefore, in the first computer run, 1,215 interdiction aircraft enter the system looking for 8,552 trucks, with a probability of .26 that an aircraft will see a truck. This produces 171 truck destructions. But, in the second computer run, when aircraft enter the system on the average of once every fifteen minutes, 2,433 interdiction aircraft search for 8,673 trucks with a probability of truck detection still at .26. This causes the destruction of 370 trucks.

The ratio of trucks destroyed to air interdiction aircraft searching for trucks is one truck per 7.1 aircraft in the first run. The ratio is one truck per 6.57 aircraft in the second run. Thus, an improved ratio is achieved for

increased aircraft arrival, but it is not significant compared to reduction in thruput. For example, from the first computer run to the second, supply thruput decreases only .55 tons per hour, even though more trucks are destroyed and network absorption is higher. Therefore, the effect of increased arrival of interdiction aircraft does not appear to be favorable when the truck interval remains constant. The reason for this can be traced back to the low probability of truck detection, the probability of truck destruction, and the relatively low tonnage carried by a truck.

The effect of more trucks entering the system will be discussed from the viewpoint of the ground transportation officer. In the first computer run, using a five minute time interval, the officer pushes 8,552 trucks through the system in 28 days and only 171 trucks are destroyed. Even when the number of aircraft over the network doubles, as accomplished in run 2, truck losses are still not relatively high (370 destroyed).

With this encouragement, the ground transportation officer doubles the average number of trucks on the road, as shown in run 3 and run 4. Run 3 is based on aircraft arrival over the link every 30 minutes, while run 4 assumes a 15 minute aircraft arrival interval. With approximately 60 trucks on the road, the probability of an aircraft detecting a truck is

$$\text{Probability (detection)} = 1 - (1-.01)^{60} = .453.$$

Comparing run 3 to run 1 reveals that supply thruput approximately doubles, even though probability of truck detection by an aircraft is .453. With a 2.5 minute time interval, 16,985 trucks enter the system and 308 are subsequently destroyed. In run 4, when aircraft arrivals are approximately once every 15 minutes, 623 trucks are destroyed out of the 17,103 that enter the system.

A comparison of the ratio of trucks destroyed to trucks which enter the system for run 2 and run 4 is revealing. In run 2, with a truck interval of five minutes, one truck is destroyed for every 23.4 that enter the system. This same ratio applied to run 4, where the truck interval is 2.5 minutes, shows one truck destroyed for every 27.4 that enter the system.

Under the conditions of this simulation, if air interdiction aircraft are only attacking trucks and the probability of truck detection is not high, it is beneficial for network users to decrease the truck departure interval. The benefits are greater thruput and a more favorable ratio of trucks destroyed to trucks which enter the system.

The final topic for analysis of the simulation is the effect truck destruction and network absorption have on network supply thruput. In run 1, network absorption accounts for 5.18 percent (3.99 percent general network absorption + 1.19 percent network defense absorption) of total system flow per hour. An indication of the effect truck destruction has on supply thruput is obtained by comparing the number of trucks destroyed to trucks entering the system. For run 1,

8,552 trucks enter the system and 1.99 percent, 171, are destroyed. Table B.4 below shows these statistics for all four runs.

Table B.4

Thruput Reduction

	Run 1	Run 2	Run 3	Run 4
Percent Trucks Destroyed	1.99	4.26	1.81	3.64
Percent Network Absorption	5.18	6.40	4.57	5.19

Another way to analyze reduction in thruput by truck destruction and network absorption is to compare the effect of increased aircraft arrivals over the link for a given truck departure interval. For analysis, we compare run 1 with run 2 and run 3 with run 4.

In run 2, average thruput flow per hour decreased .45 tons per hour (19.90 - 19.45). Network absorption accounts for .24 tons per hour (1.31 - 1.07). The remaining .21 tons per hour cannot be attributed solely to truck destruction. Part of the .21 tons per hour must be attributed to interspersing of more support trucks in the network flow. Comparing run 3 to run 4 in like manner shows a decrease in average network flow per hour of .85 tons. Network absorption accounts for .24 tons per hour (2.13 - 1.89). The remainder of the .61 tons per hour is a combination of truck destruction and support truck interspersement.

In summary, we see that network thruput is not significantly reduced by increased AAA support or increased truck destruction. This information would allow network defenders to construct additional AAA sites should interdiction aircraft become more effective in detecting and destroying trucks.

We ran the simulation described above on the CREATE computer system at the School of Systems and Logistics (AFIT) at Wright-Patterson AFB, Ohio. The AFIT/SL version of GASP IIB was used. Included in this appendix is a listing of our user's program for the one link network interdiction simulation. Also, we include a description of the Non-GASP variables, the program parameters, codes for statistics collected, a description of the events file, and the input data for the first run.

Non-GASP Variables

Variable Name	Description
NUM	Counter for number of enroute trucks
D	Probability of detecting a lone truck (0.01)
AVTFLO	Average total system flow/hour
AVSPFL	Average support flow/hour
PCTGEN	Percent flow absorbed by general support
PCTAAA	Percent flow absorbed by AAA support
ITRK	Number of trucks destroyed
TLAST	Time last truck arrived
ALAST	Time last aircraft arrived
SUPP	Accumulated general support used

AAA	Accumulated AAA support used
TYPE	Random number to determine truck type (one ton or two ton)
TBT	Time between trucks
RNUM	Random number to determine number of attacks
TBA	Time between aircraft
NATK	Number of attacks (0,1,2,3)
DETECT	Indicator for truck detection (1-detected; 0- non-detected)
KILL	Indicator for trucks destroyed (1-destroyed; 0-no damage)
DES	Random number to determine column in NSET of destroyed truck
C	Probability interval for each enroute truck in NSET
A	Lower limit of probability interval for scanned column of NSET
B	Upper limit of probability interval for scanned column of NSET

<u>Program Parameters</u>

Truck Arrivals	Constant	Param (1) 5. .Ø .Ø .Ø
Truck Travel Time (minutes)	Normal Distribution	Param (2) 15Ø. 14Ø. 16Ø. 2.Ø
Aircraft Arrival	Lognormal Dist.	Param (3) 27. 34. - 0.
Truck Support (tons)	Constant	Param (4) 0.05 0.075
AAA at Attack Aircraft (tons)	Normal Distribution	Param (5) .075 .025 .125 .0125
AAA at Over-flight (tons)	Normal Distribution	Param (6) .025 0. .05 .0063

Number of Attack Passes Probabilities	Probability Mass Function	Param (7) .08 .39 .85 1.0
Number of Attacks	Probability Mass Function	Param (8) 0 1 2 3
Kill Probability Per Attack	Probability Mass Function	Param (9) .4 .25 .15

File 1 - Events File

Attribute		Description
1		Scheduled time of event
2	event codes	1. Truck enters system 2. Truck departs system 3. Aircraft enters system 4. End of simulation
3	truck type	1. One ton truck of thruput 2. Two ton truck of thruput 11. One ton truck of support material 12. Two ton truck of support material

Codes for Collected Statistics

COLCT 1 - Amount of thruput departing link

COLCT 2 - Amount of support material for the link

COLCT 3 - Amount of general support demand

COLCT 4 - Amount of AAA support demand

COLCT 5 - Time between truck arrivals

COLCT 6 - Time between aircraft arrivals

COLCT 7 - Total trucks destroyed

GASP IIB INPUT DATA

```
BEAU*ROB        512 41973   4
   9     1     7     0    80     3     1    22       1000.
  20
   1
   1
 5.
 150.       140.        160.        2.0
 27.        34.
 0.05       0.075
 0.075      0.025       0.125       0.0125
 0.025      0.0         0.05        0.0063
 0.08       0.39        0.85        1.0
 0.         1.          2.          3.
 0.4        0.25        0.15
    0     1     1     7        0.0                     3.     0
      -1
       12.        2.        1.
       11.        3.        0.
       10.5       1.        2.
       110320.    4.        0.
       0
    0     1     1     7        0.0                     4.     0
      -1
       12.        2.        1.
       11.        3.        0.
       10.5       1.        2.
       110320.    4.        0.
       0
    0     1     1     7        0.0                     5.     0
      -1
       12.        2.        1.
       11.        3.        0.
       10.5       1.        2.
       110320.    4.        0.
       0
    0     1     0     7        0.0                     6.     0
      -1
       12.        2.        1.
       11.        3.        0.
       10.5       1.        2.
       110320.    4.        0.
       0
```

```
C    ***GASP IIB INTERDICTION SIMULATION***
DIMENSION NSET(10,80)
C   **SELECT GASP COMMON CARDS**
$:SELECTA:CARDGSP
COMMON TLAST,ALAST,TYPE,NUM,SUPP,AAA,D
COMMON AVTFLO,AVSPFL,PCTGEN,PCTAAA,ITRK
NUM=1
D=0.01
AVTFLO=0.
AVSPFL=0.
PCTGEN=0.
PCTAAA=0.
ITRK=0
TLAST=0.
ALAST=0.
SUPP=0.
AAA=0.
CALL GASP2B(NSET)
STOP
END
```

```
SUBROUTINE EVNTS(IX,NSET)
DIMENSION NSET(10,1)
C   **SELECT GASP COMMON CARDS**
$:SELECTA:CARDGSP
COMMON TLAST,ALAST,TYPE,NUM,SUPP,AAA,D
COMMON AVTFLO,AVSPFL,PCTGEN,PCTAAA,ITRK
GO TO (1,2,3,4),IX
1 CALL TRKARR(NSET)
RETURN
2 CALL TRKDEP(NSET)
RETURN
3 CALL AIRCRAFT(NSET)
RETURN
4 CALL ENDSM(NSET)
RETURN
END
```

```
SUBROUTINE TRKARR(NSET)
DIMENSION NSET(10,1)
C   **SELECT GASP COMMON CARDS**
$:SELECTA:CARDGSP
COMMON TLAST,ALAST,TYPE,NUM,SUPP,AAA,D
COMMON AVTFLO,AVSPFL,PCTGEN,PCTAAA,ITRK
TBT=TNOW-TLAST
IF(TNOW.LT.240.)GO TO 1
CALL COLCT(TBT,5,NSET)
1 TLAST=TNOW
```

```
ATRIB(1)=TNOW+RNORM(2)
ATRIB(2)=2.
CALL FILEM(1,NSET)
NUM=NUM+1
IF(ATRIB(3).GT.2.)GO TO 2
ATRIB(1)=TNOW+PARAM(1,1)
ATRIB(2)=1.
TYPE=DRAND(SEED)
IF(TYPE.LE.0.3)ATRIB(3)=1.
IF(TYPE.GT.0.3)ATRIB(3)=2.
CALL FILEM(1,NSET)
2 RETURN
END
```

```
SUBROUTINE TRKDEP(NSET)
DIMENSION NSET(10,1)
C  **SELECT GASP COMMON CARDS**
$:SELECTA:CARDGSP
COMMON TLAST,ALAST,TYPE,NUM,SUPP,AAA,D
COMMON AVTFLO,AVSPFL,PCTGEN,PCTAAA,ITRK
NUM=NUM-1
IF(ATRIB(3).GT.2.)GO TO 1
TYPE=ATRIB(3)
IF(TNOW.LT.240.)GO TO 6
CALL COLCT(TYPE,1,NSET)
6 GO TO 2
1 TYPE=ATRIB(3)-10.
IF(TNOW.LT.240.)GO TO 2
CALL COLCT(TYPE,2,NSET)
2 J=TYPE
SUPP=SUPP+PARAM(4,J)
IF(TNOW.LT.240.)GO TO 7
CALL COLCT(PARAM(4,J),3,NSET)
7 IF(SUPP-2.)4,3,3
3 SUPP=SUPP-2.
ATRIB(1)=TNOW+30.
ATRIB(2)=1.
TYPE=DRAND(SEED)
IF(TYPE.LE.0.3)GO TO 5
ATRIB(3)=12.
CALL FILEM(1,NSFT)
4 RETURN
5 ATRIB(3)=11.
CALL FILEM(1,NSET)
ATRIB(1)=TNOW+33.
CALL FILEM(1,NSET)
GO TO 4
END
```

```
SUBROUTINE AIRCRAFT(NSET)
DIMENSION NSET(10,1)
C  **SELECT GASP COMMON CARDS**
$:SELECTA:CARDGSP
COMMON TLAST,ALAST,TYPE,NUM,SUPP,AAA,D
COMMON AVTFLO,AVSPFL,PCTGEN,PCTAAA,ITRK
TBA=TNOW-ALAST
IF(TNOW.LT.240.)GO TO 14
CALL COLCT(TBA,6,NSET)
CALL HISTO(TBA,13.,1.,1)
14 ALAST=TNOW
ATRIB(1)=TNOW+RLOGN(3)
CALL FILEM(1,NSET)
IF(DRAND(SEED).LE.0.01)RETURN
RNUM=DRAND(SEED)
DO 1 I=1,4
IF(PARAM(7,I)-RNUM)1,2,2
1 CONTINUE
2 NATK=PARAM(8,I)
IF(NATK.EQ.0)GO TO 9
DETECT=0.
IF(NUM.EQ.0)GO TO 3
IF(DRAND(SEED).LE.(1-(1-D)**NUM))DETECT=1.
3 KILL=0.
DO 8 I=1,NATK
IF(DETECT.EQ.0.)GO TO 6
IF(DRAND(SEED).LE.PARAM(9,NATK))KILL=1.
IF(KILL.EQ.0.)GO TO 7
IF(TNOW.LT.240.)GO TO 17
CALL COLCT(1.,7,NSET)
17 DES=DRAND(SEED)
C=1./NUM
A=0.
B=C
DO 4 KCOL=1,ID
IF(NSET(2,KCOL).NE.2000)GO TO 4
IF(DES.GT.A.AND.DES.LE.B)GO TO 5
A=A+C
B=B+C
4 CONTINUE
5 CALL RMOVE(KCOL,1,NSET)
NUM=NUM-1
IF(ATRIB(3).LT.3.)GO TO 6
ATRIB(1)=TNOW+30.
ATRIB(2)=1.
CALL FILEM(1,NSET)
6 KILL=0.
DETECT=0.
IF(NUM.EQ.0)GO TO 7
IF(DRAND(SEED).LE.(1-(1-D)**NUM))DETECT=1.
7 AA=RNORM(5)
IF(TNOW.LT.240.)GO TO 15
CALL COLCT(AA,4,NSET)
15 AAA=AAA+AA
```

```
5 CONTINUE
GO TO 10
9 AA=RNORM(6)
IF(TNOW.LT.240.)GO TO 16
CALL COLCT(AA,4,NSET)
16 AAA=AAA+AA
10 IF(AAA-2.)12,11,11
11 AAA=AAA-2.
ATRIB(1)=TNOW+30.
ATRIB(2)=1.
TYPE=DRAND(SEED)
IF(TYPE.LE.0.3)GO TO 13
ATRIB(3)=12.
CALL FILEM(1,NSET)
12 RETURN
13 ATRIB(3)=11.
CALL FILEM(1,NSET)
ATRIB(1)=TNOW+33.
CALL FILEM(1,NSET)
GO TO 12
END
```

```
SUBROUTINE ENDSM(NSET)
DIMENSION NSET(10,1)
C  **SELECT GASP COMMON CARDS**
$:SELECTA:CARDGSP
COMMON TLAST,ALAST,TYPE,NUM,SUPP,AAA,D
COMMON AVTFLO,AVSPFL,PCTGEN,PCTAAA,ITRK
AVTFL=(SUMA(1,1)+SUMA(2,1))/168.
AVTFLO=AVTFLO+AVTFL
AVSPF=SUMA(2,1)/168.
AVSPFL=AVSPFL+AVSPF
PCTGE=SUMA(3,1)/(SUMA(1,1)+SUMA(2,1))*100.
PCTGEN=PCTGEN+PCTGE
PCTAA=SUMA(4,1)/(SUMA(1,1)+SUMA(2,1))*100.
PCTAAA=PCTAAA+PCTAA
ITR=SUMA(7,1)
ITRK=ITRK+ITR
PRINT 100,AVTFL
100 FORMAT( //24X,"AVE TOTAL SYSTEM FLOW PER HOUR",11X,
&F7.2,1X,"TON")
PRINT 150,AVSPF
150 FORMAT( /24X,"AVE SUPPORT FLOW PER HOUR",16X,
&F7.2,1X,"TON")
PRINT 200,PCTGE
200 FORMAT( /24X,"PERCENT FLOW ABSORBED BY GENERAL",
&" SUPPORT",F8.2," %")
PRINT 250,PCTAA
250 FORMAT( /24X,"PERCENT FLOW ABSORBED BY AAA",13X,
&F7.2," %")
PRINT 300,ITR
```

```
300 FORMAT( /24X,"TOTAL TRUCKS DESTROYED DURING WEEK",
&7X,I4)
IF(NRUNS-1)2,2,1
1 MSTOP= -1
NORPT=1
CALL SUMRY(NSET)
NUM=1
TLAST=0.
ALAST=0.
SUPP=0.
AAA=0.
RETURN
2 MSTOP= -1
NORPT=0
RETURN
END
```

```
SUBROUTINE OTPUT(NSET)
DIMENSION NSET(10,1)
C  **SELECT GASP COMMON CARDS**
$:SELECTA:CARDGSP
COMMON TLAST,ALAST,TYPE,NUM,SUPP,AAA,D
COMMON AVTFLO,AVSPFL,PCTGEN,PCTAAA,ITRK
AVTFLO=AVTFLO/NRUN
AVSPFL=AVSPFL/NRUN
PCTGEN=PCTGEN/NRUN
PCTAAA=PCTAAA/NRUN
PRINT 50,NRUN
50 FORMAT( //37X,"SUMMARY TOTAL OF",I3,1X,"WEEKS")
PRINT 100,AVTFLO
100 FORMAT( /24X,"AVE TOTAL SYSTEM FLOW PER HOUR",11X,
&F7.2,1X,"TON")
PRINT 150,AVSPFL
150 FORMAT( /24X,"AVE SUPPORT FLOW PER HOUR",16X,
&F7.2,1X,"TON")
PRINT 200,PCTGEN
200 FORMAT( /24X,"PERCENT FLOW ABSORBED BY GENERAL",
&" SUPPORT",F8.2," %")
PRINT 250,PCTAAA
250 FORMAT( /24X,"PERCENT FLOW ABSORBED BY AAA",13X,
&F7.2," %")
PRINT 300,ITRK
300 FORMAT( /24X,"TOTAL TRUCKS DESTROYED",19X,I4)
RETURN
END
```

BIBLIOGRAPHY

1. Amme, Carl H. "Crisis of Confidence," United States Naval Institute Proceedings, March 1964.

2. Ashley, Roger M., Captain, USAF. "Toward a Generalized Measure of Effectiveness for Anti-Capacity Interdiction." Unpublished Master's thesis, Graduate School of Systems and Logistics, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, 1973.

3. Capps, Larry R., Major, USA. "A Dynamic Model for the Allocation of Airstrikes Against a Lines-of-Communication Network." Unpublished Master's thesis, Naval Postgraduate School, Monterey, California, September 1970.

4. Durbin, Eugene P. An Interdiction Model of Highway Transportation. The RAND Corporation, RM-4945-PR, May 1966.

5. Fisher, Edward J., Major, USAF. "An Algorithm for Determining Thruput in Small Capacitated Networks." Technical Report No. SLTR 1-73, prepared at School of Systems and Logistics, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, January 1973.

6. ________, and Captain Gerald R. McNichols, USAF. "Unclassified Excerpts from Developing Measures of Effectiveness for Air Interdiction (U)." Paper presented at the 24th Meeting of the Military Operations Research Society, San Diego, California, November 20, 1969.

7. Graves, Gary L., Captain, USAF, and Shirley Roy. "The CREATE Version of GERTS IIIZ." Unpublished Master's thesis, Graduate School of Systems and Logistics, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, September 1972.

8. Helmbold, Robert L. A Countercapacity Network Interdiction Model. The RAND Corporation, R-611-PR, March 1971.

Preceding page blank

9. Higgins, J. W. Concepts, Data Requirements and Uses of the LOC Interdiction Model as Applied to North Vietnam. The RAND Corporation, RM-6065-PR, May 1970.

10. Kast, Fremont E., and James E. Rosenzweig. Organization and Management: A Systems Approach. New York: McGraw-Hill, Inc., 1970.

11. Mustin, Thomas M., Lieutenant, USN. "Optimal Allocation of Air Strikes for Interdiction of a Transportation Network." Unpublished Master's thesis, Naval Postgraduate School, Monterey, California, June 1967.

12. Nosenzo, L. V. "An Approach to the Tradeoff of Tactical Air and Ground Forces." Paper prepared for Assistant Chief of Staff Studies and Analysis (AFCSA) Hq., Air Force Systems Command, Washington, D.C., March 1969.

13. Pritsker, Alan B., and Phillip J. Kiviat. Simulation With GASP II: A FORTRAN Based Simulation Language. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1969.

14. Sallagar, F. M. Operation "Strangle" (Italy, Spring 1944): A Case Study of Tactical Air Interdiction. The RAND Corporation, R-851-PR, February 1972.

15. U.S. Department of the Air Force. U.S. Air Force Glossary of Standardized Terms. AFM-11-1, Vol. I. Washington, D.C.: U.S. Government Printing Office, 1 January 1973.

16. Van Horn, Richard L. "Validation of Simulation Results," Management Science. Vol. 17, No. 5, January 1971.

17. Wagner, Harvey M. Principles of Management Science: With Applications to Executive Decisions. Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1970.

18. Wollmer, Richard D. Some Methods for Determining the Most Vital Link in a Railway Network. The RAND Corporation, RM-3321-ISA, April 1963.

19. ________. "Removing Arcs from a Network," Operations Research. Vol. 12, No. 6, November-December 1964.